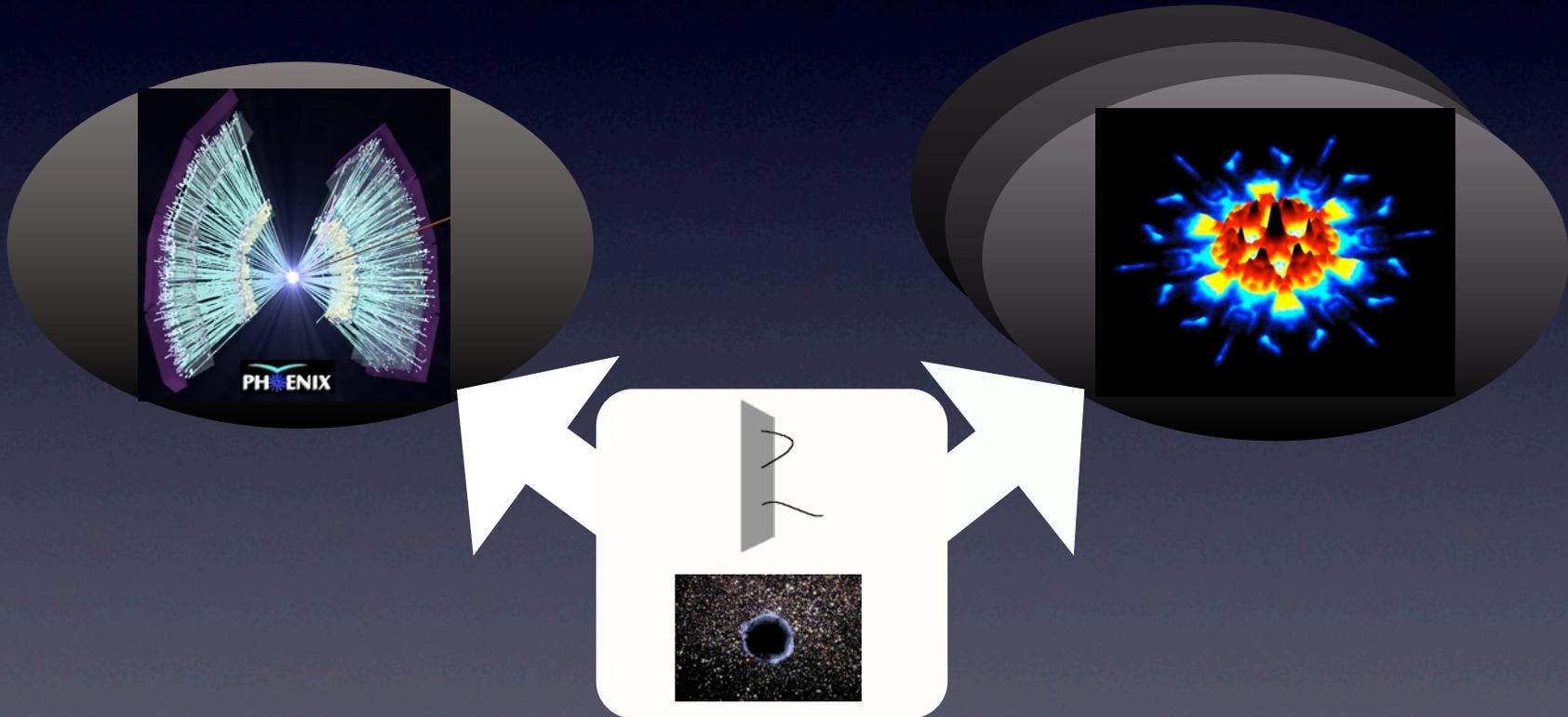


A Theory of Everything at Strong Coupling

RIKEN Lunch Seminar, RIKEN BNL Research Center, Brookhaven, February 21, 2013



Matthias Kaminski (University of Washington, Seattle)

A winding path ...

2002-2004: Low temperature experiments,
computational physics & statistical mechanics

2004-2005: Collider phenomenology

[Diploma Thesis (2005)]

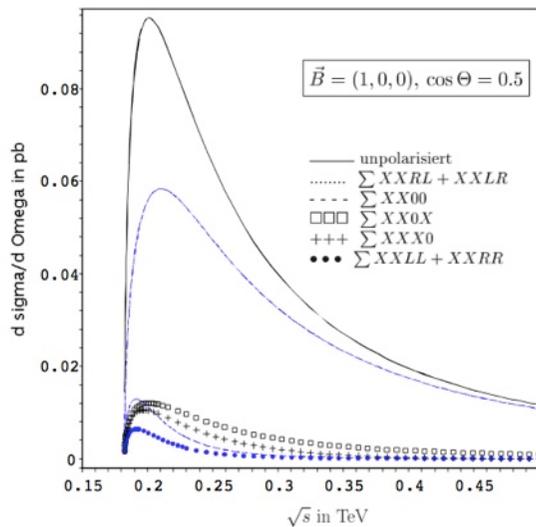


A winding path ...

2002-2004: Low temperature experiments, computational physics & statistical mechanics

2004-2005: Collider phenomenology

[Diploma Thesis (2005)]



```
module dsigma_module
use kinds
use ctq6Pdf_module
implicit none
public
real (kind = double) :: sLS, costh1LS

contains
function Ctq6Pdf(x,x,mz) result (dsigma_res)
end function Ctq6Pdf

contains
function dsigma(x, weights, channel, grids)
use kinds
use vamp_grid_type
implicit none
real (kind = double), dimension(:), intent(in) :: x
real(kind=double), dimension(:), intent(in) :: weights
integer, intent(in), optional :: channel
type(vamp_grid), dimension(:), intent(in), optional :: grids
real (kind = double) :: dsigma_res,dsigma_res
&dsigma_resu,x1,x2,sinthew,costhew
real (kind = double) :: i
!!!!!! COMPHEP SM Parameters
real (kind = double), parameter :: Alpha = 0.127
real (kind = double), parameter :: e = 0.3134
real (kind = double), parameter :: mz = 0.091
real (kind = double), parameter :: sinw = 0.4
real (kind = double), parameter :: cosw = 0.8
real (kind = double), parameter :: GAMMAz = 0.007

* k1thetak2
global k1thk2=the;
id q1(0)=ss/2;
id q1(1)=ss/2*sinth*cosph;
id q1(2)=ss/2*sinth*sinph;
id q1(3)=ss/2*costh;

id q2(0)=ss/2;
id q2(1)=-ss/2*sinth*cosph;
id q2(2)=-ss/2*sinth*sinph;
id q2(3)=-ss/2*costh;
id ss^2=S;

bracket L,S;
*print;
.sort;
.store;

** epsilon with 3 momenta
**theta(q4,nu)*e_(q1,q2,q3,nu)
```



A winding path ...

2002-2004: Low temperature experiments,
computational physics & statistical mechanics

2004-2005: Collider phenomenology

[Diploma Thesis (2005)]

2005-2006: String theory



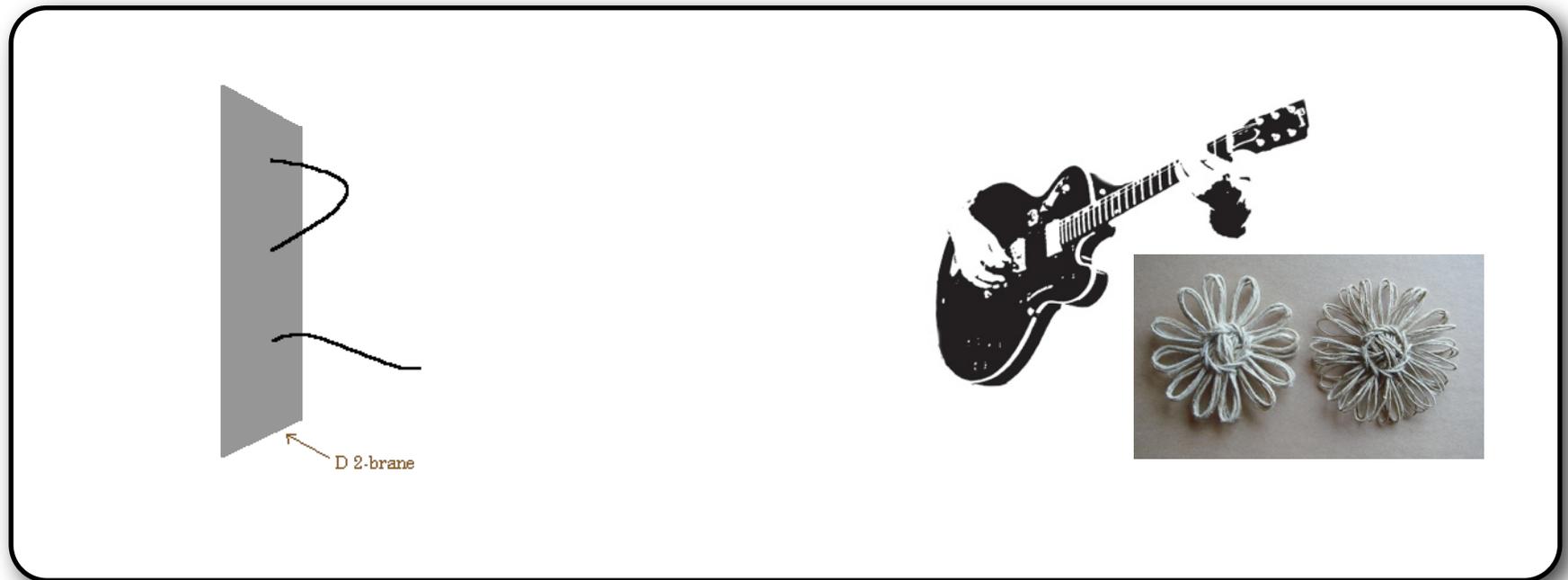
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2006-2010: Gauge/gravity correspondence

[PhD Thesis (2008)]



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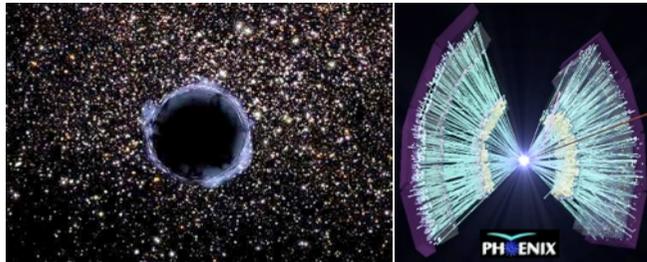
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“AdS/QCD”



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2010-2013: Systems at strong coupling



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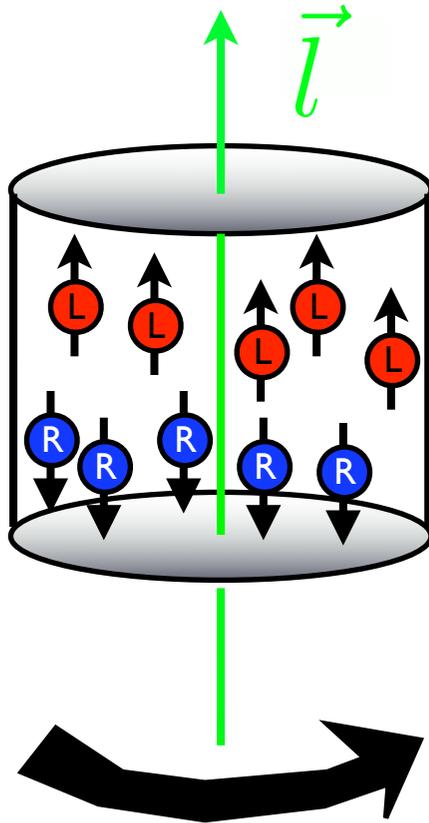
- ✓ Formal investigation of fundamental principles.
- ✓ Make predictions to be compared to experiments.



Chiral vortical effect

[Erdmenger, Haack, MK, Yarom; JHEP (2009)]

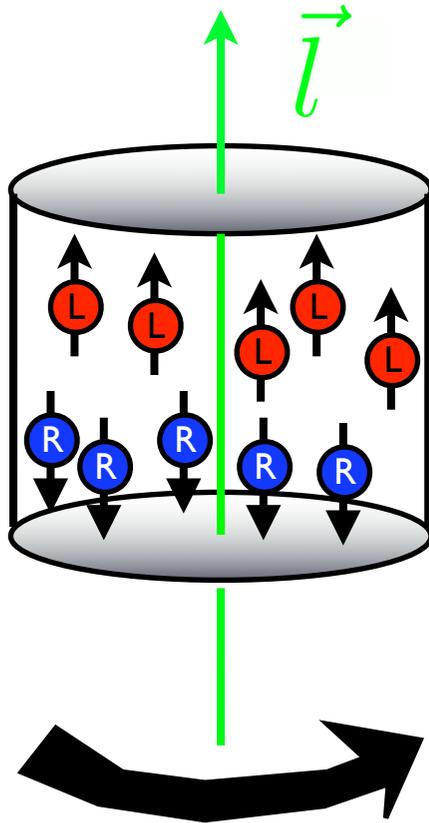
*Holographic model of
relativistic quantum fluid*



Chiral vortical effect

[Erdmenger, Haack, MK, Yarom; JHEP (2009)]

*Holographic model of
relativistic quantum fluid*



*later: field theory
understanding*

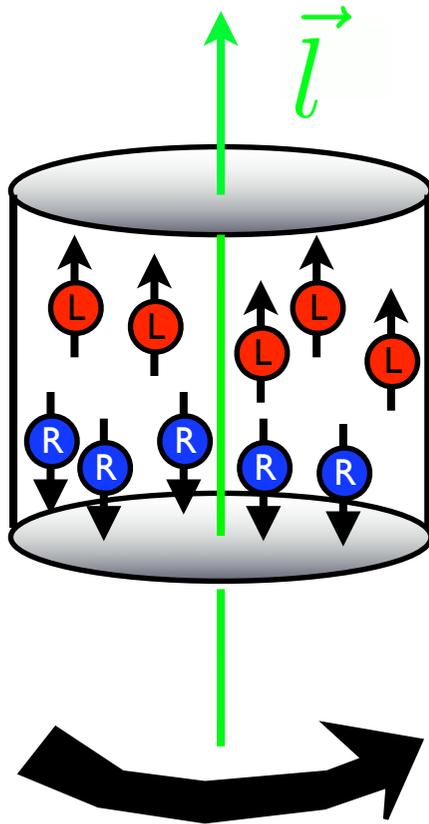
[Son, Surowka; PRL (2009)]



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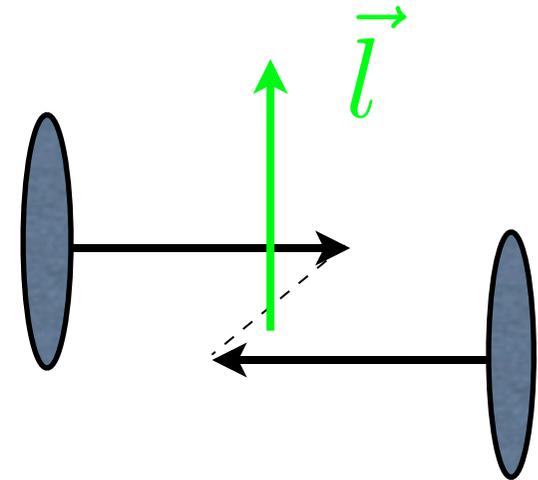
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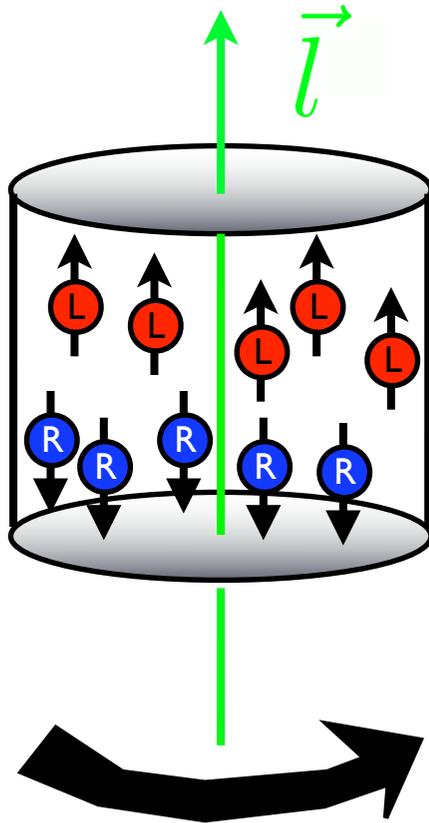
Heavy ion collision



Chiral vortical effect

[Erdmenger, Haack, MK, Yarom; JHEP (2009)]

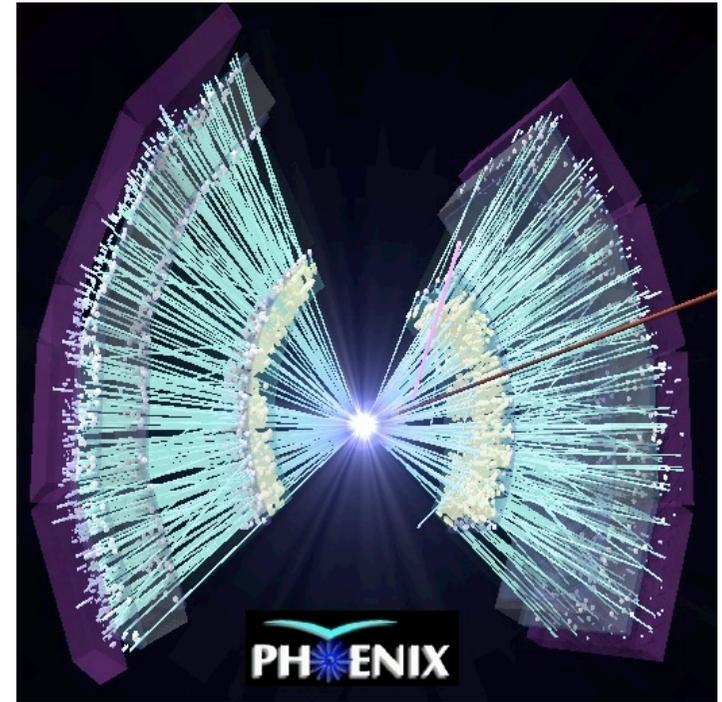
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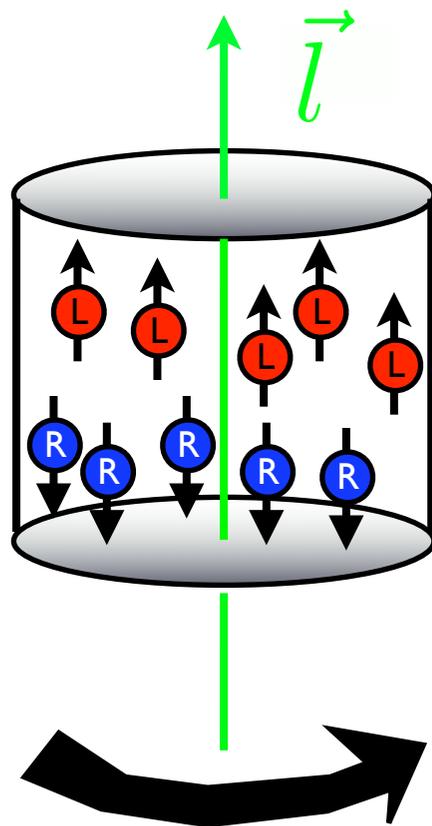
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Chiral vortical effect

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Holographic model of relativistic quantum fluid



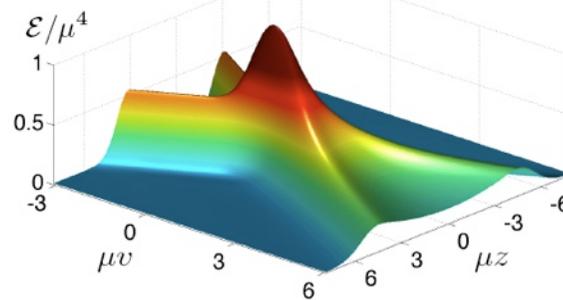
later: field theory understanding

[Son, Surowka; PRL (2009)]

Solvable holographic toy model of Heavy ion collision

Quantum fluid far-from-equilibrium with anomaly

[Fuini, MK, Yaffe (work in progress)]



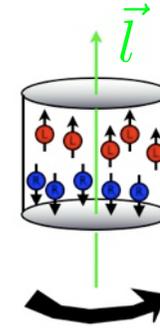
[Chesler, Yaffe; PRL (2011)]

later: field theory understanding ...

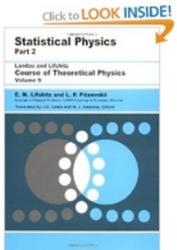


Outline

I. Discovering the chiral vortical effect



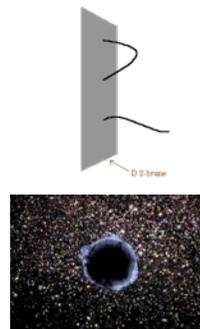
II. Formal discoveries in an old theory: relativistic hydrodynamics with anomalies



III. Thermalization: non-equilibrium models

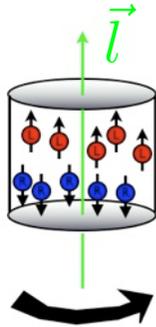


IV. Putting strings to use



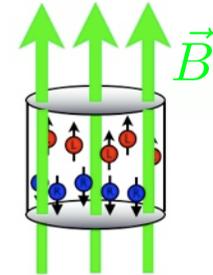
Chiral transport effects history

Chiral
vortical
effect



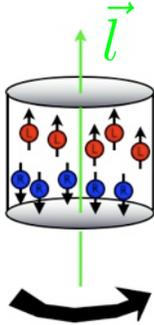
[Erdmenger, Haack, MK, Yarom;
JHEP (2009)]

Chiral
magnetic
effect



Chiral transport effects history

Chiral
vortical
effect



[Erdmenger, Haack, MK, Yarom;
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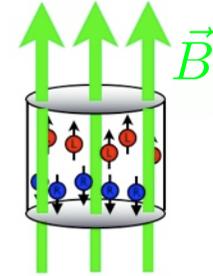
[[arXiv:0809.2488](https://arxiv.org/abs/0809.2488)]

[Kharzeev, McLerran, Warringa;
Nucl.Phys.A (2008)]

[Kharzeev, Zhitnitsky; *Nucl.Phys.A*
(2007)]

[Vilenkin; ... (1979)]

Chiral
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[Fukushima et al.; *PRD* (2008)]

[Kharzeev et al.; *Nucl.Phys.A* (2007)]

[Kharzeev; *Phys.Lett.B* (2006)]

[[arXiv:hep-ph/0406125](https://arxiv.org/abs/hep-ph/0406125)]

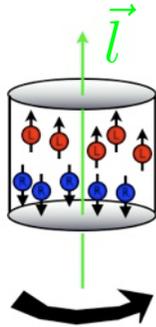
[...]

[Son, Surowka; *PRL* (2009)]



Chiral transport effects history

Chiral
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[Erdmenger, Haack, MK, Yarom;
JHEP (2009)]

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[Kharzeev, Zhitnitsky; *Nucl.Phys.A*
(2007)]

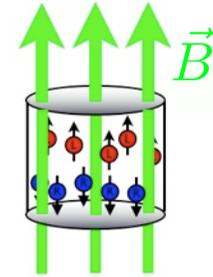
[...]

[Vilenkin; ... (1979)]

[Son, Surowka; *PRL* (2009)]

Any relativistic quantum system with anomalous
currents exhibits chiral effects.

Chiral
magnetic
effect



[Fukushima et al.; *PRD* (2008)]

[Kharzeev et al.; *Nucl.Phys.A* (2007)]

[Kharzeev; *Phys.Lett.B* (2006)]

[arXiv:hep-ph/0406125]

[...]



Not in non-relativistic
classical fluids



Hydrodynamics

Universal effective field theory, expansion in gradients of temperature, chemical potential and velocity

- fields $T(x), \mu(x), u^\nu(x)$

- conservation equations

$$\nabla_\mu T^{\mu\nu} = F^{\nu\lambda} j_\lambda$$

$$\nabla_\nu j^\nu = 0$$

- constitutive equations (Landau frame)

Energy momentum tensor

$$T^{\mu\nu} = \epsilon u^\mu u^\nu + P(g^{\mu\nu} + u^\mu u^\nu) + \tau^{\mu\nu}$$

Conserved current

$$j^\mu = n u^\mu + \nu^\mu$$



New transport effect in hydrodynamics

Relativistic quantum liquid with one conserved charge and U(1) **anomaly**

Gauge/gravity computation yields ...

Conservation equations:

$$\nabla_{\mu} T^{\mu\nu} = F^{\nu\lambda} j_{\lambda}$$

$$\nabla_{\mu} j^{\mu} = C E^i B_i$$



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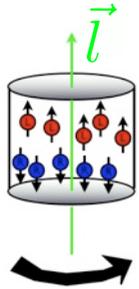
Constitutive equations (Landau frame):

Energy momentum tensor

$$T^{\mu\nu} = \frac{\epsilon}{3} (4u^{\mu} u^{\nu} + g^{\mu\nu}) + \tau^{\mu\nu}$$

Anomalous current

$$j^{\mu} = nu^{\mu} - \sigma T (g^{\mu\nu} + u^{\mu} u^{\nu}) \partial_{\nu} \left(\frac{\mu}{T} \right) + \xi \omega^{\mu}$$



$$\omega^{\mu} = \frac{1}{2} \epsilon^{\mu\nu\lambda\rho} u_{\nu} \nabla_{\lambda} u_{\rho}$$

Chiral vortical effect from gauge/gravity computation

[Erdmenger, Haack, MK, Yarom; JHEP (2009)]

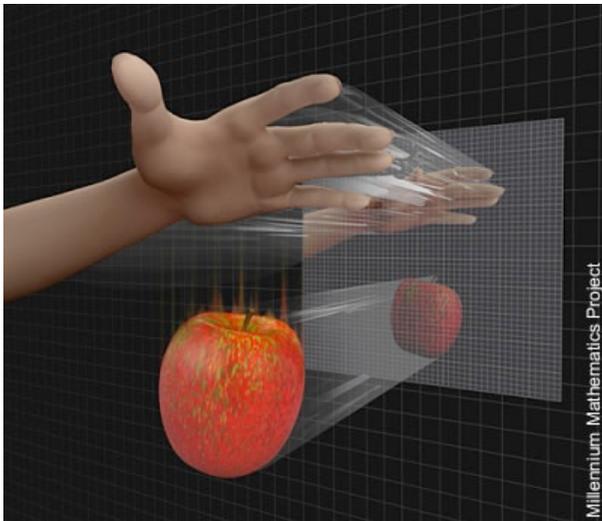


Gauge/gravity concepts

Gauge/gravity correspondence is based on the **holographic principle**. [*t Hooft (1993)*]

A priori the **gauge/gravity correspondence** has nothing to do with string theory.

String theory is an example. [*Susskind (1995)*]
[*Maldacena (1998)*]



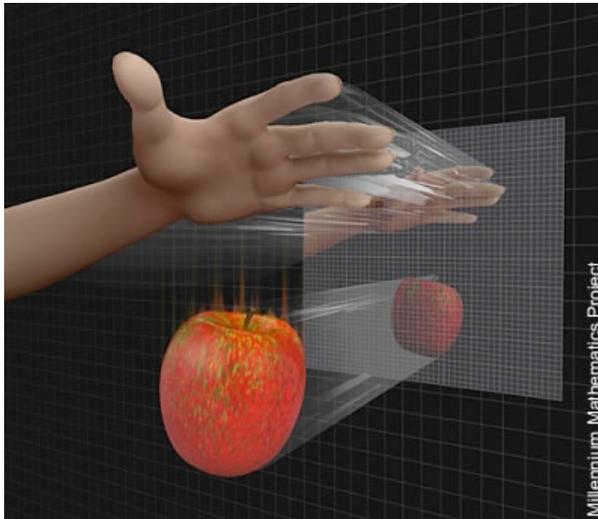
Gauge/gravity concepts

strongly coupled
quantum field theory

correspondence



weakly curved gravity



Millennium Mathematics Project

radial AdS
coordinate

Anti-de Sitter
space
boundary



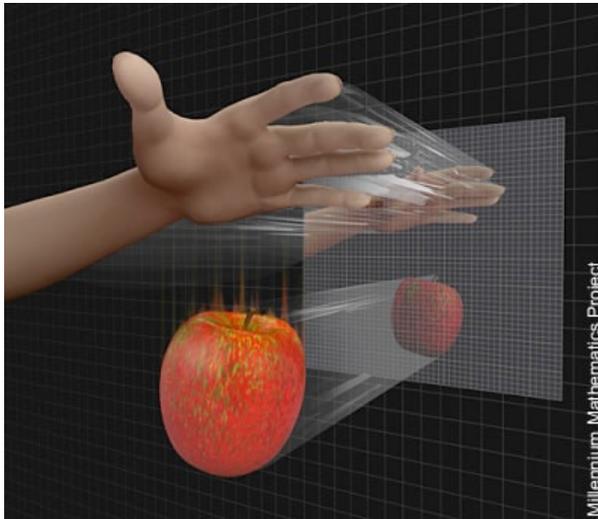
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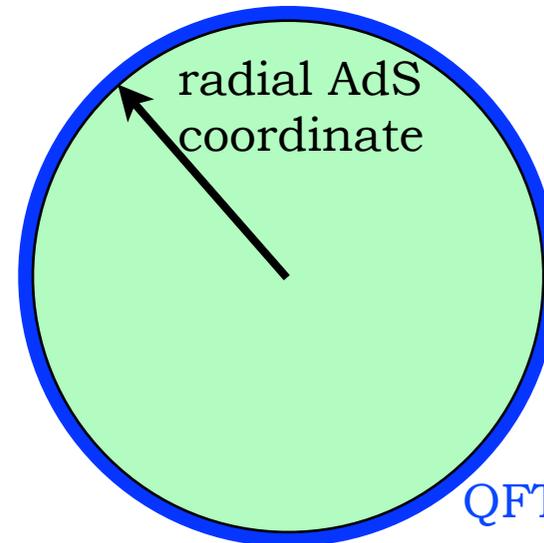
correspondence



weakly curved gravity



Millennium Mathematics Project



Anti-de Sitter
space
boundary

QFT



Gauge/gravity concepts

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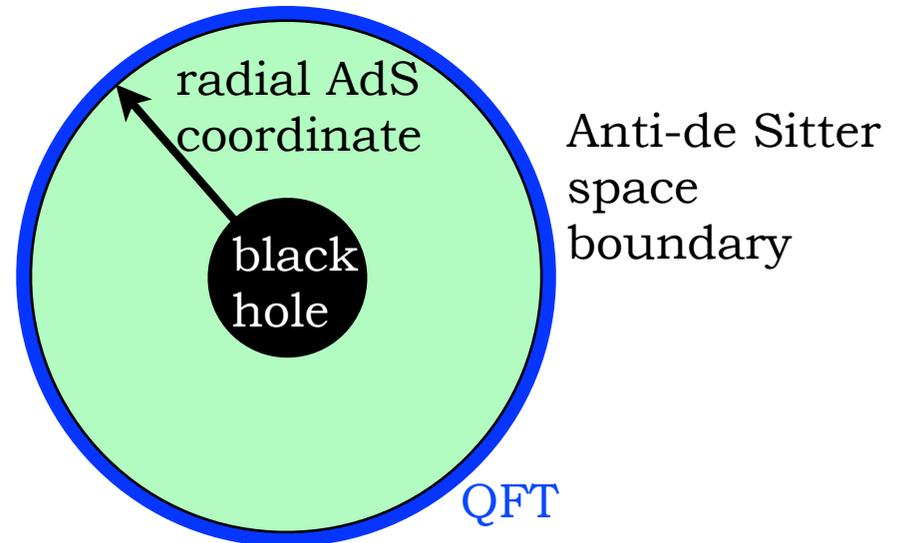
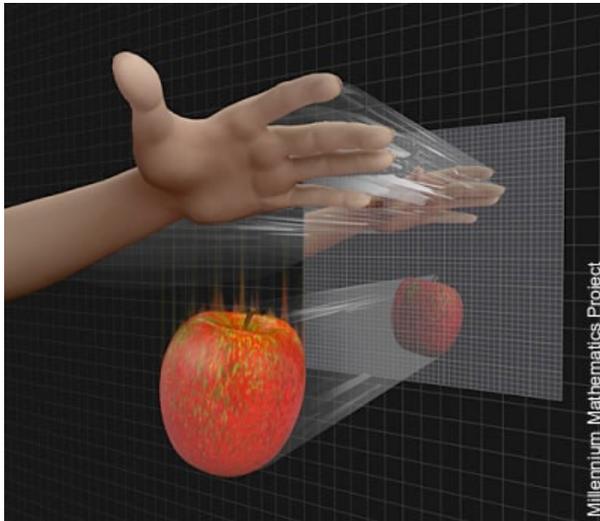


weakly curved gravity

QFT temperature



Hawking temperature



Gauge/gravity concepts

strongly coupled
quantum field theory

correspondence



weakly curved gravity

QFT temperature

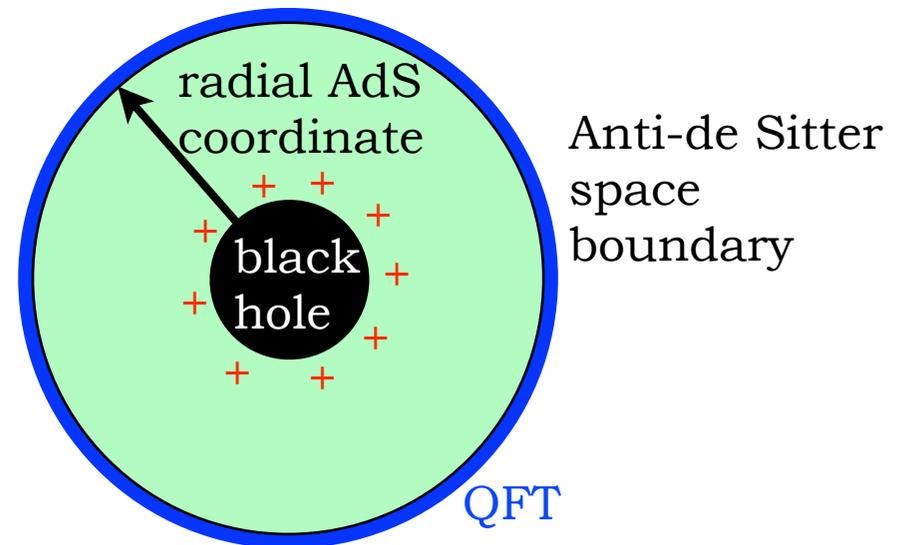
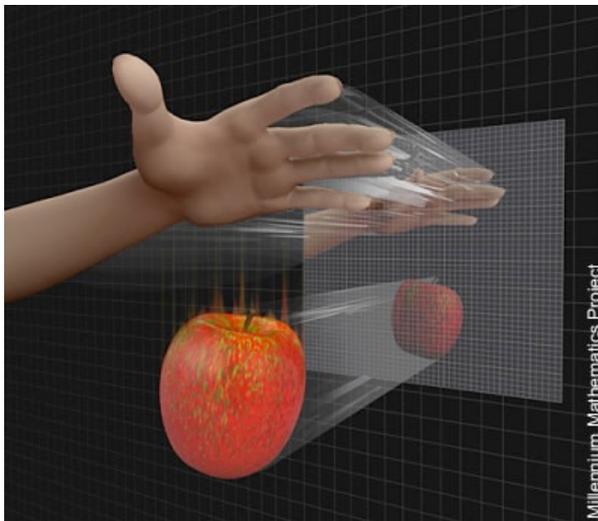


Hawking temperature

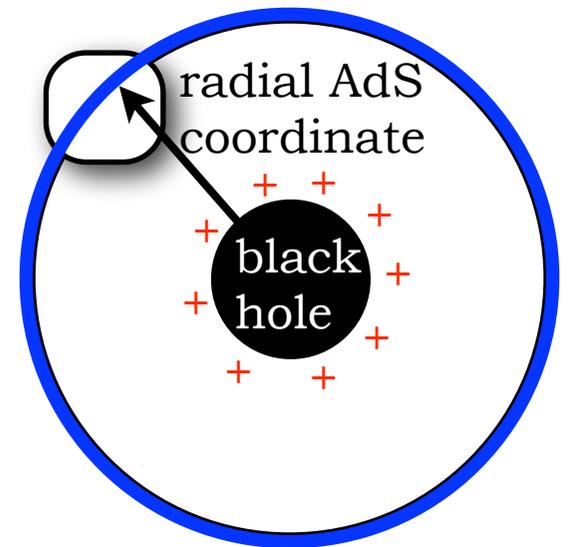
conserved **charge**



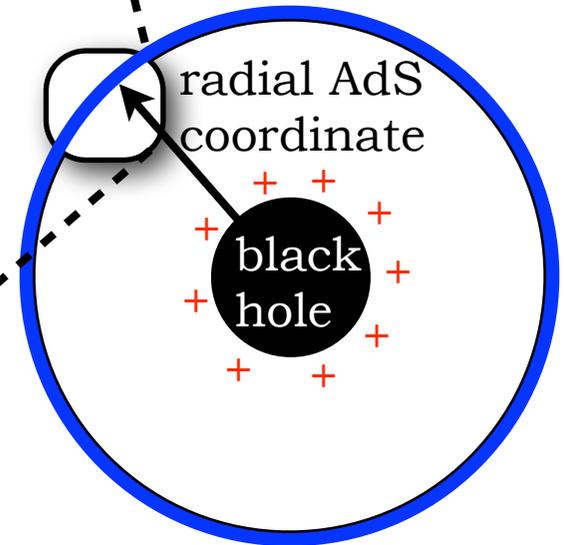
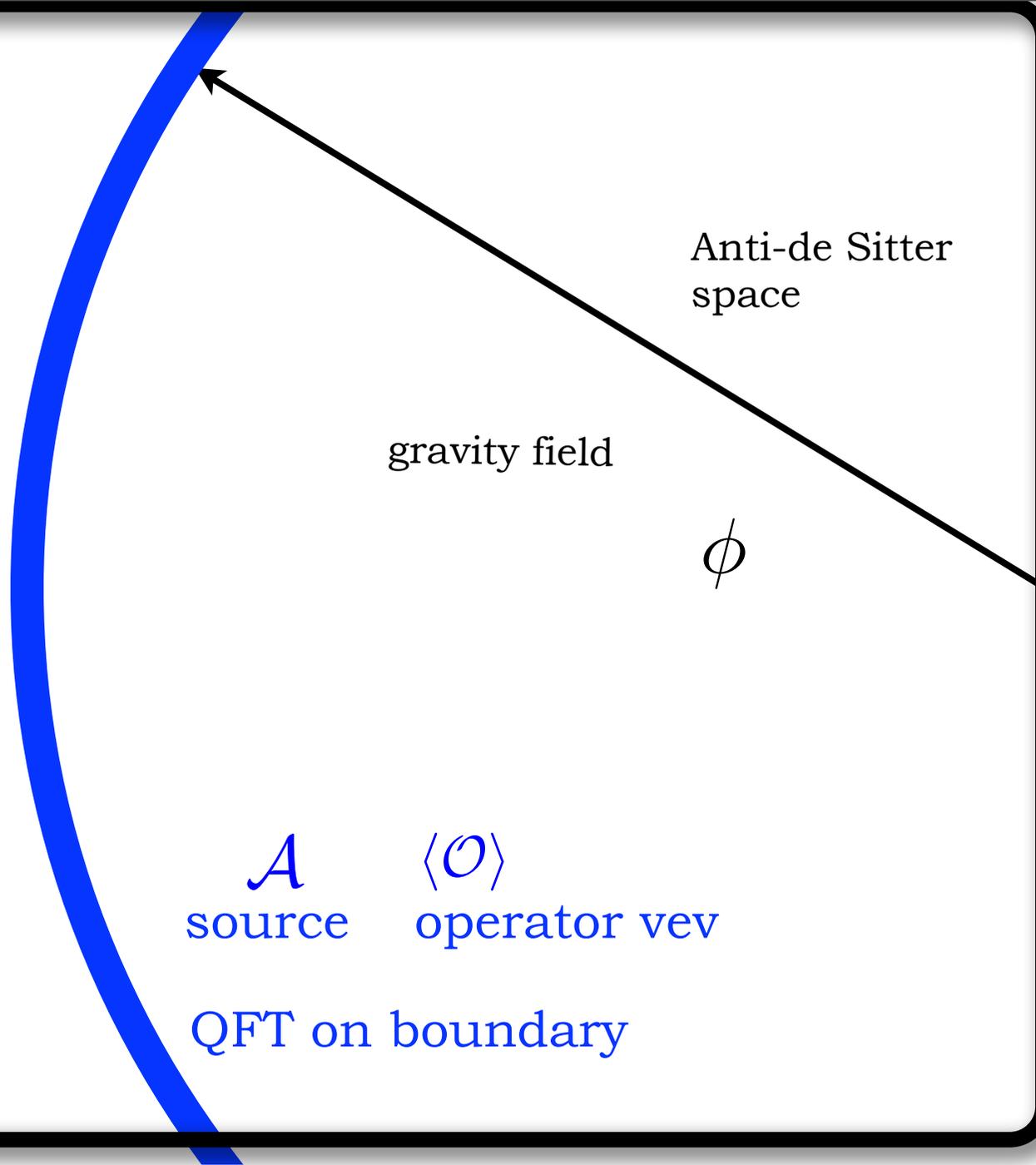
charged black hole



Correspondence by zooming in on boundary



Correspondence by zooming in on boundary



Correspondence by zooming in on boundary

Anti-de Sitter space

gravity field

$$\phi = \phi(0) + \phi(1) \frac{1}{r} + \phi(2) \frac{1}{r^2} + \dots$$

\mathcal{A} source $\langle \mathcal{O} \rangle$ operator vev

QFT on boundary

radial AdS coordinate



black hole



Correspondence by zooming in on boundary

Anti-de Sitter space

gravity field

$$\phi = \phi_{(0)} + \phi_{(1)} \frac{1}{r} + \phi_{(2)} \frac{1}{r^2} + \dots$$

*mathematical map:
gauge/gravity
correspondence*



\mathcal{A}

$\langle \mathcal{O} \rangle$

source

operator vev

QFT on boundary

radial AdS coordinate



black hole

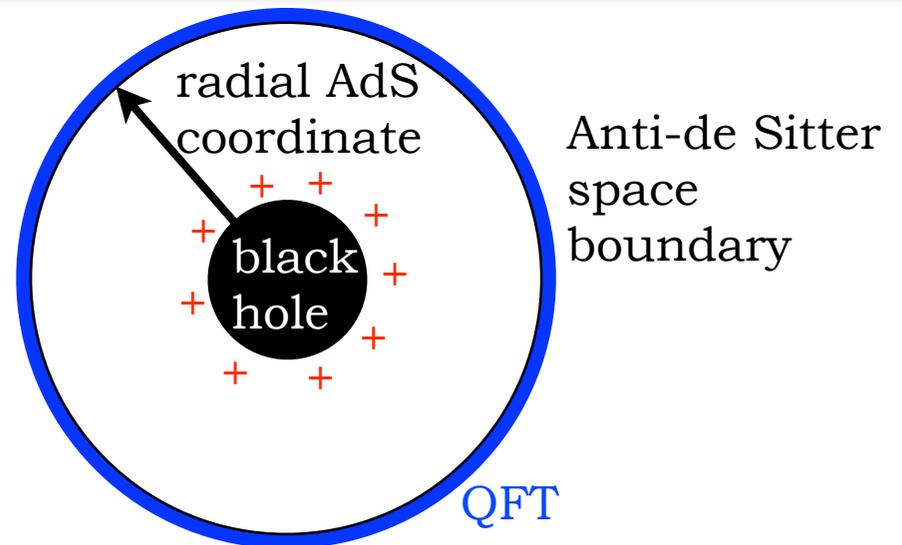


Fluid/gravity correspondence

[Bhattacharyya et al.; JHEP (2008)]

Einstein equations = hydrodynamic conservation equations + dynamical equations of motion

Constitutive equations from geometry near boundary.



Example: $N=4$ Super-Yang-Mills with $U(1)$

[Erdmenger, Haack, MK, Yarom; JHEP (2009)]

Gravity dual: 5-dimensional Einstein-Maxwell-Chern-Simons action (with negative cosmological constant)

$$S = -\frac{1}{2\kappa_5^2} \int \left[\sqrt{-g} \left(R + 12 - \frac{1}{4} F^2 \right) - \frac{1}{12\sqrt{3}} \epsilon^{MNO PQ} A_M F_{NO} F_{PQ} \right] d^4x dr$$



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CS-term dual to chiral anomaly



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CS-term dual to chiral anomaly

Black hole with R-charge (in Eddington-Finkelstein coordinates):

$$ds^2 = -r^2 f(r) u_\mu u_\nu dx^\mu dx^\nu + r^2 \Delta_{\mu\nu} dx^\mu dx^\nu - 2u_\mu dx^\mu dr$$

$$f(r) = 1 + \frac{Q^2}{r^6} - \frac{1}{b^4 r^4} \quad A_r = 0, \quad A_\mu = -\frac{\sqrt{3}Q}{r^2} u_\mu \quad \Delta_{\mu\nu} = \eta_{\mu\nu} + u_\mu u_\nu$$



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solution with constant parameters Q, b, u^μ .

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Make parameters boundary-coordinate-dependent: *dual to hydrodynamic fields*

$$b \rightarrow b(x), \quad Q \rightarrow Q(x), \quad u^\mu \rightarrow u^\mu(x)$$

- expand in gradients of b, Q and u
dual to hydrodynamic expansion in the field theory
- new analytical solutions to Einstein equations
give values of transport coefficients in field theory



Gauge/gravity result

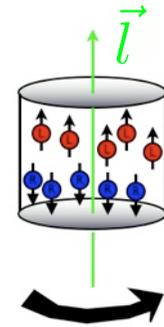
$$\begin{aligned} \partial_r (r^5 f(r) \partial_r \pi_{ij}^{(n)}) &= \mathbf{P}_{ij}^{(n)}(r) \\ \partial_r (r^5 \partial_r j_i^{(n)}(r) + 2\sqrt{3} Q_0 a_i^{(n)}(r)) &= \mathbf{J}_i^{(n)}(r) \\ 3\partial_r S^{(n)}(r) - \frac{3}{2} r^{-1} \partial_r (r^2 \partial_r h^{(n)}(r)) &= \mathbf{S}^{(n)}(r) \\ \partial_r (r^4 k^{(n)}(r)) + 8r^3 S^{(n)}(r) + b_0^{-4} (1 - 3r^4 b_0^4) \partial_r h^{(n)}(r) - \frac{2}{\sqrt{3}} Q_0 \partial_r c^{(n)} &= \mathbf{K}^{(n)}(r) \\ \partial_r (r^3 \partial_r c^{(n)}) - 2\sqrt{3} Q_0 \partial_r S^{(n)} + 3\sqrt{3} Q_0 \partial_r h^{(n)} &= \mathbf{C}^{(n)}(r) \\ \partial_r (r^3 f(r) \partial_r a_i^{(n)}(r) + 2\sqrt{3} L Q_0 a_i^{(n)}(r)) &= \mathbf{A}_i^{(n)}(r) \end{aligned}$$

*gives you
all there is
in the model*

$$\Rightarrow j^\mu = n u^\mu - \sigma T (g^{\mu\nu} + u^\mu u^\nu) \partial_\nu \left(\frac{\mu}{T} \right) + \xi \omega^\mu$$

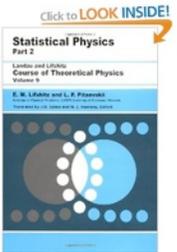
$$\xi = \tilde{C}(\mu, n) \mu^2 \quad \omega^\mu = \frac{1}{2} \epsilon^{\mu\nu\lambda\rho} u_\nu \nabla_\lambda u_\rho$$

\Rightarrow Chiral vortical effect
for a **particular model** QFT
with a chiral anomaly



Navigator

- I. Discovering the chiral vortical effect
- II. Formal discoveries in an old theory: relativistic hydrodynamics with anomalies
- III. Thermalization: non-equilibrium models
- IV. Putting strings to use



Hydrodynamic computation

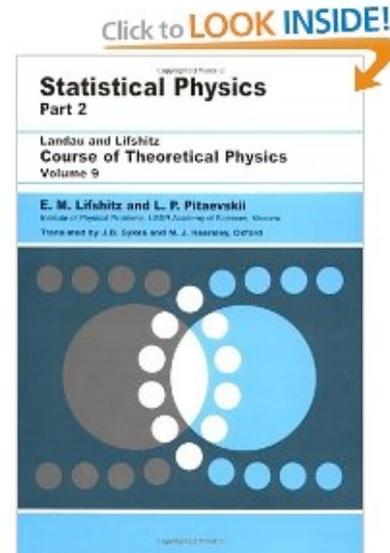
Textbook method

[Landau, Lifshitz]

1. Constitutive equations: all (pseudo)vectors and (pseudo)tensors under Lorentz group

Old example: $\nabla_\nu u^\nu$

New example: $\omega^\mu = \frac{1}{2} \epsilon^{\mu\nu\lambda\rho} u_\nu \nabla_\lambda u_\rho$ (vorticity)



Hydrodynamic computation

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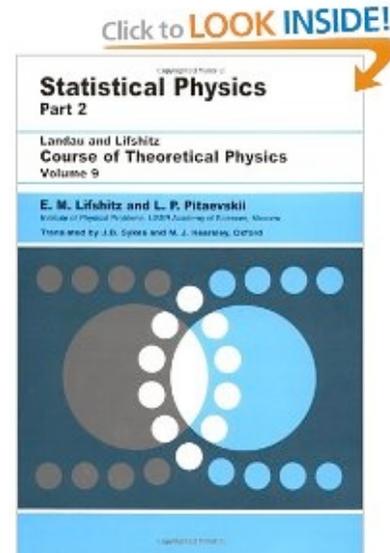
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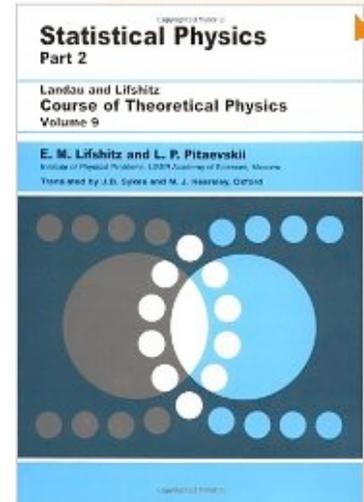


Hydrodynamic computation

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Click to **LOOK INSIDE!**



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$$\nabla_\mu J_s^\mu \geq 0$$

[Landau, Lifshitz]

Example: $\nabla_\mu J_s^\mu = \dots + \frac{1}{T} \zeta (\nabla_\nu u^\nu)^2 + \dots \geq 0$



Hydrodynamic result

For any QFT with a chiral anomaly

[Son, Surowka; PRL (2009)]

Generalized constitutive equations **with external fields**

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu + P g^{\mu\nu} - \eta \Delta^{\mu\alpha} \Delta^{\nu\beta} (\partial_\alpha u_\beta + \partial_\beta u_\alpha) - (\zeta - \frac{2}{3}\eta) \Delta^{\mu\nu} \nabla_\gamma u^\gamma$$

$$j^\mu = nu^\mu + \sigma V^\mu + \xi \omega^\mu + \xi_B B^\mu$$

vorticity *magnetic field*

$$\left\{ \begin{array}{l} V^\mu = E^\mu - T \Delta^{\mu\nu} \nabla_\nu \left(\frac{\mu}{T} \right) \\ E^\mu = F^{\mu\nu} u_\nu \\ B^\mu = \frac{1}{2} \epsilon^{\mu\nu\alpha\beta} u_\nu F_{\alpha\beta} \\ \omega^\mu = \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} u_\nu \nabla_\rho u_\sigma \end{array} \right.$$



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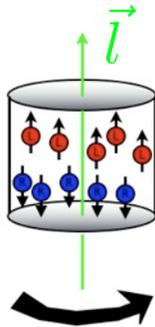
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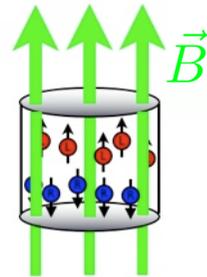
New transport coefficients

$$\xi = C \left(\mu^2 - \frac{2}{3} \frac{n\mu^3}{\epsilon + P} \right), \quad \xi_B = C \left(\mu - \frac{1}{2} \frac{n\mu^2}{\epsilon + P} \right)$$

chiral
vortical
effect



chiral
magnetic
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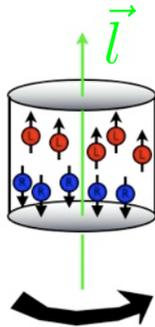
Gauge/gravity result
(no external fields)

$$\xi = \tilde{C}(\mu, n) \mu^2$$

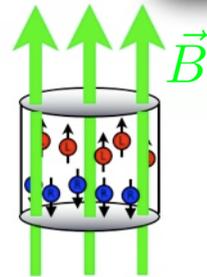
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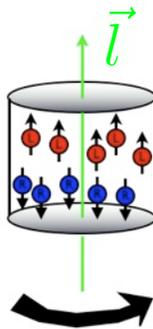
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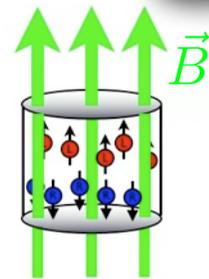
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chiral
vortical
effect



chiral
magnetic
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Observable in heavy ion
collisions?

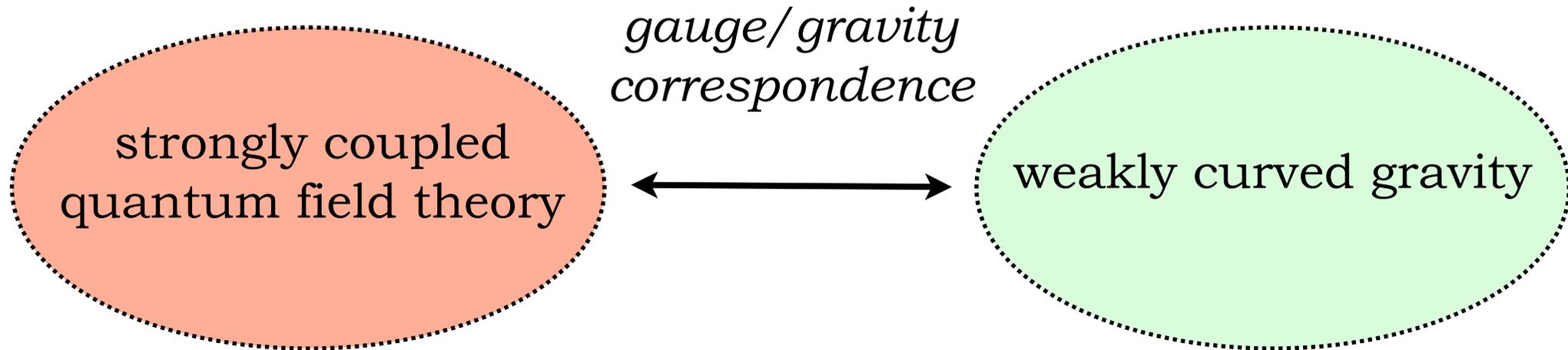
[Kharzeev, Son.; PRL (2011)]

(collaboration in progress: [Bleicher, MK, Petersen])

[Bleicher, MK, Schaffner-Bielich])



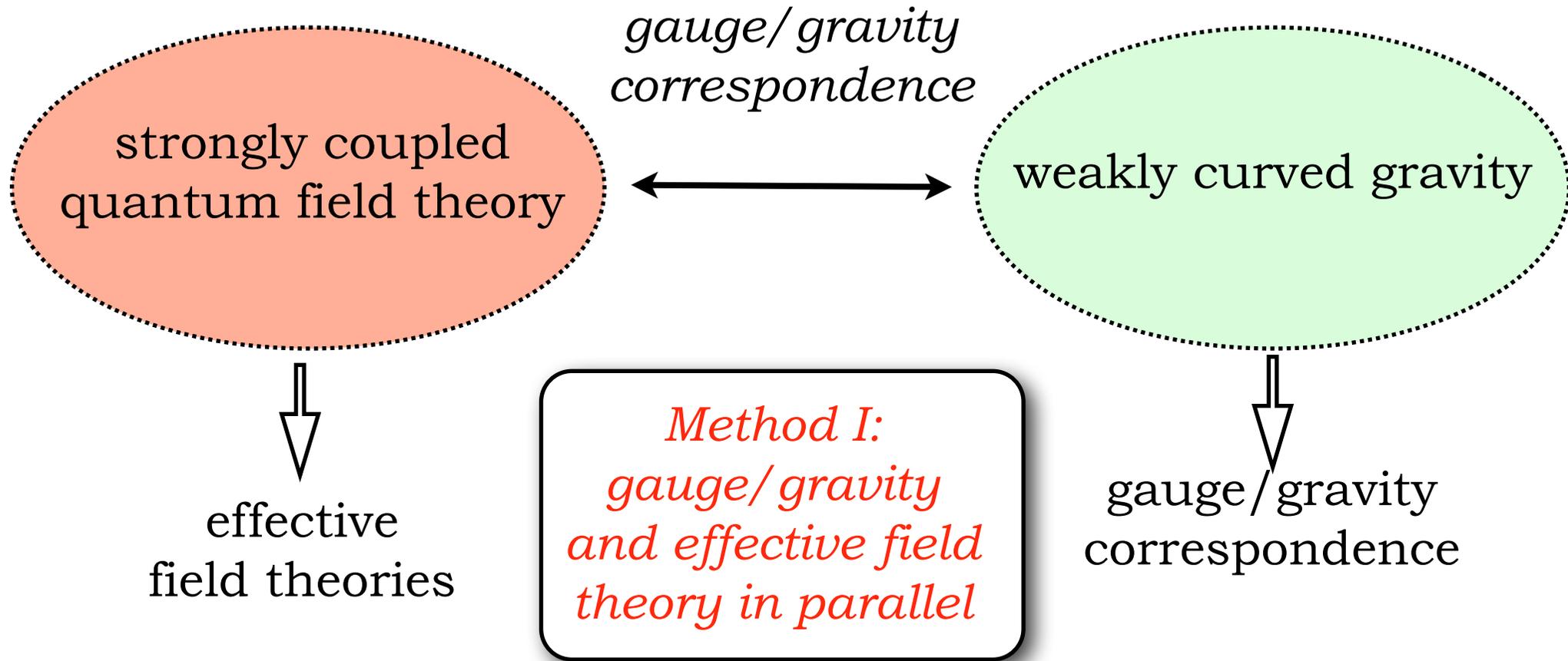
Methods



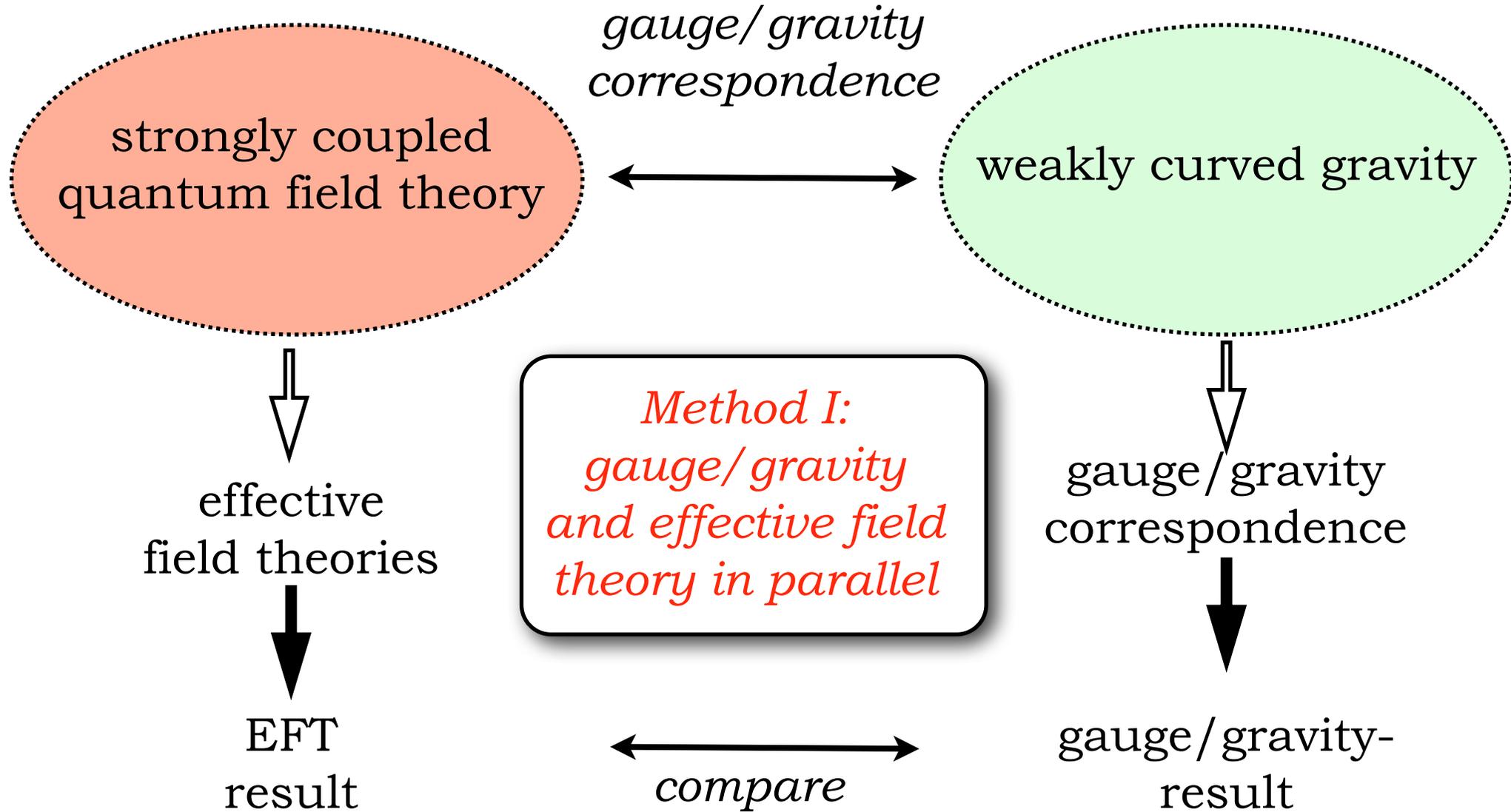
*Method I:
gauge/gravity
and effective field
theory in parallel*



Methods



Methods



Refined chiral vortical effect

$$\xi = C \left(\mu^2 - \frac{2}{3} \frac{\mu^3 n}{\epsilon + P} \right) + \dots$$

*formal
approach
guarantees
completeness*



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More than one anomalous current

$$\nabla_\nu J_a^\nu = \frac{1}{8} C_{abc} \epsilon^{\nu\rho\sigma\gamma} F_{\nu\rho}^b F_{\sigma\gamma}^c$$

$$\xi_a = C_{abc} \mu^b \mu^c + 2\beta_a T^2 - \frac{2n_a}{\epsilon + p} \left(\frac{1}{3} C_{bcd} \mu^b \mu^c \mu^d + 2\beta_b \mu^b T^2 + \gamma T^3 \right)$$

[Neiman, Oz; JHEP (2010)]



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various charges

previously
set to zero

[Neiman, Oz; JHEP (2010)]

$$\beta = -4\pi^2 c_m$$

[Jensen, Loganayagam, Yarom; (2012)]



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Gravitational anomalies

[Jensen, Loganayagam, Yarom; (2012)]

$$\nabla_\nu T_{cov}^{\mu\nu} = F^\mu{}_\nu J_{cov}^\nu + \frac{c_m}{2} \nabla_\nu \left[\epsilon^{\rho\sigma\alpha\beta} F_{\rho\sigma} R^{\mu\nu}{}_{\alpha\beta} \right]$$

full transport coefficient
exactly known for
standard model



Formal aside I: Hydrodynamics

Traditional method

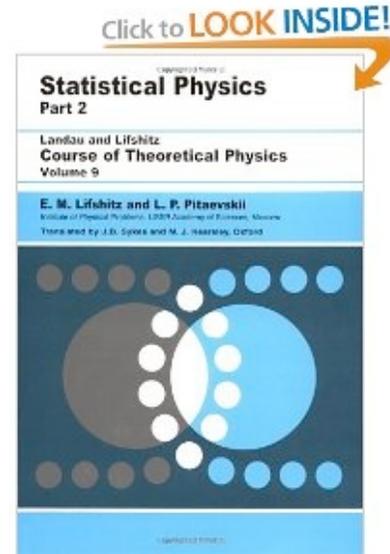
[Landau, Lifshitz]

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2. Restricted by conservation equations

3. Further restricted by **positivity of local entropy production:**

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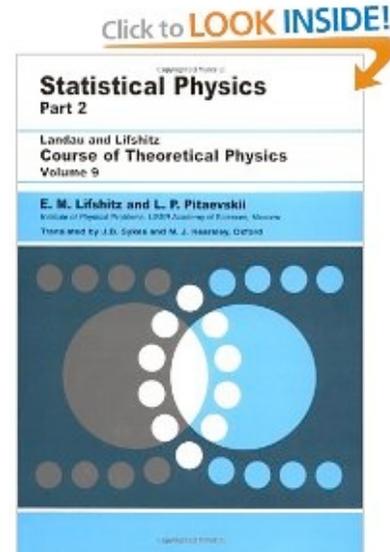


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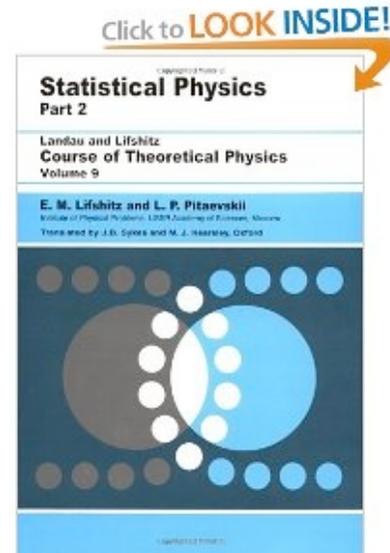


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3. Further restricted by **positivity of**

Replace by restrictions for hydrodynamic two-point-functions

Proof in 2+1 dimensions:

[Jensen, MK, Kovtun, Meyer, Ritz, Yarom; JHEP (2012)]

Proof for “equality type” conditions in D dimensions:

[Jensen, MK, Kovtun, Meyer, Ritz, Yarom; PRL (2012)]

Formal aside II: New restrictions for EFTs

Two-point-functions

$$\text{Example: } \langle j^x j^x \rangle = \frac{\delta \langle j^x \rangle}{\delta A_x} = \frac{i\omega^2 \sigma}{\omega + iDk^2} + \dots$$

a) Analyticity conditions

b) Onsager relations

c) Equilibrium relations

d) Ward identities



Formal aside II: New restrictions for EFTs

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a) Analyticity conditions

b) Onsager relations

c) Equilibrium relations

[Jensen, MK, Kovtun, Meyer, Ritz, Yarom; PRL (2012)]

New construction principle for effective actions.

d) Ward identities

a), b), c), d) conjectured to be equivalent
to entropy current argument.

[Jensen, MK, Kovtun, Meyer, Ritz, Yarom; JHEP (2012)]



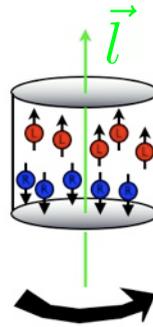
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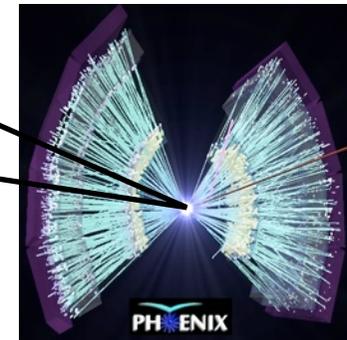
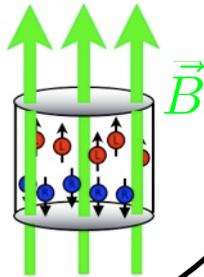


Chiral effects in experiments?

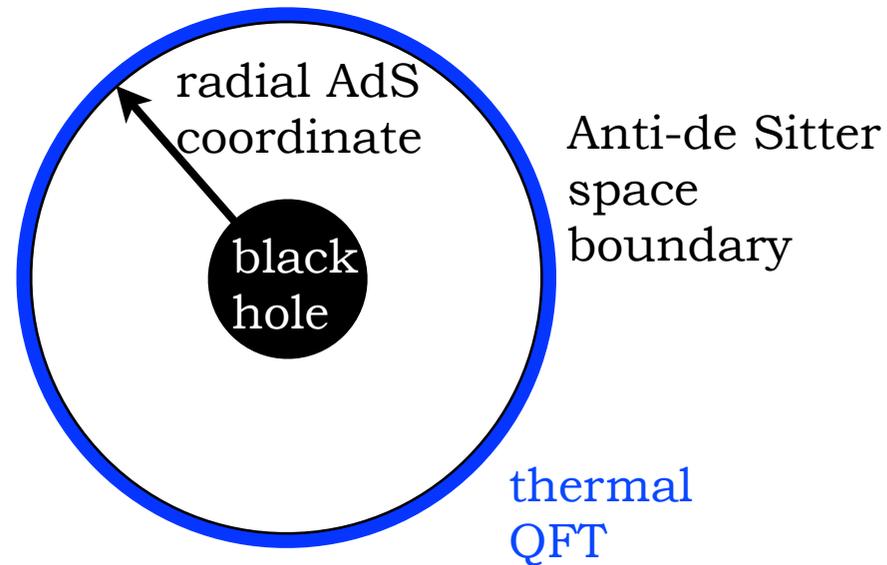
*Chiral
vortical
effect*



*Chiral
magnetic
effect*

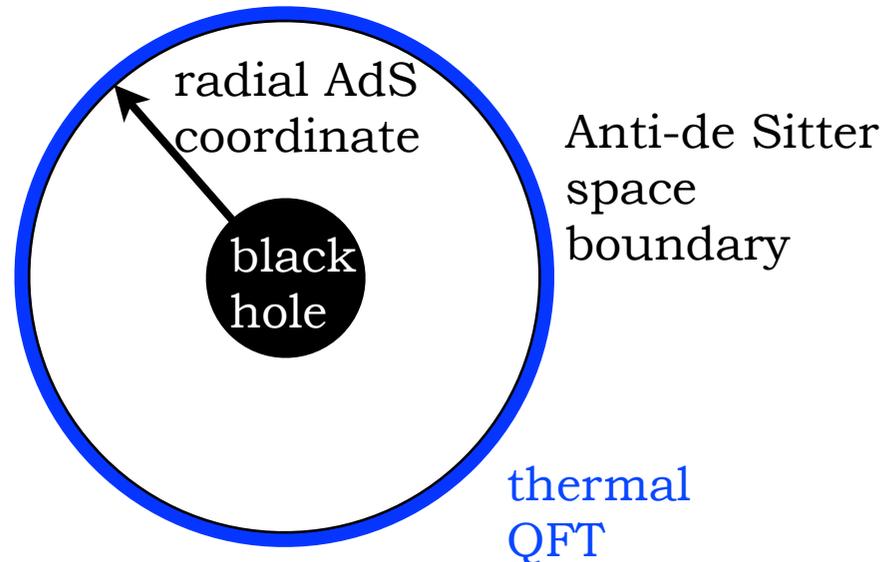
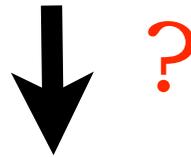
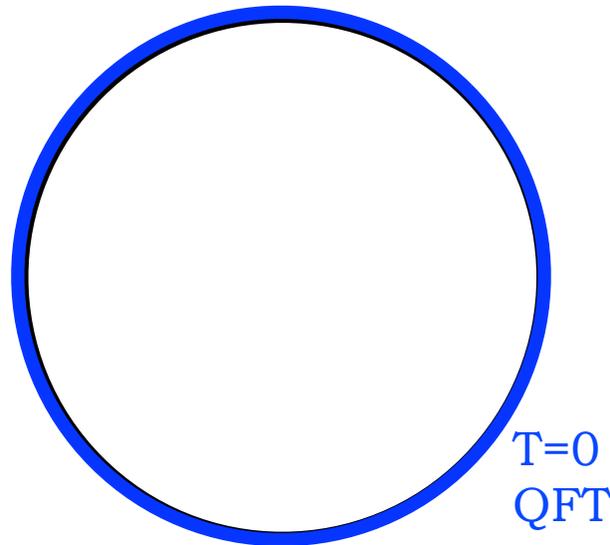


Holographic thermalization

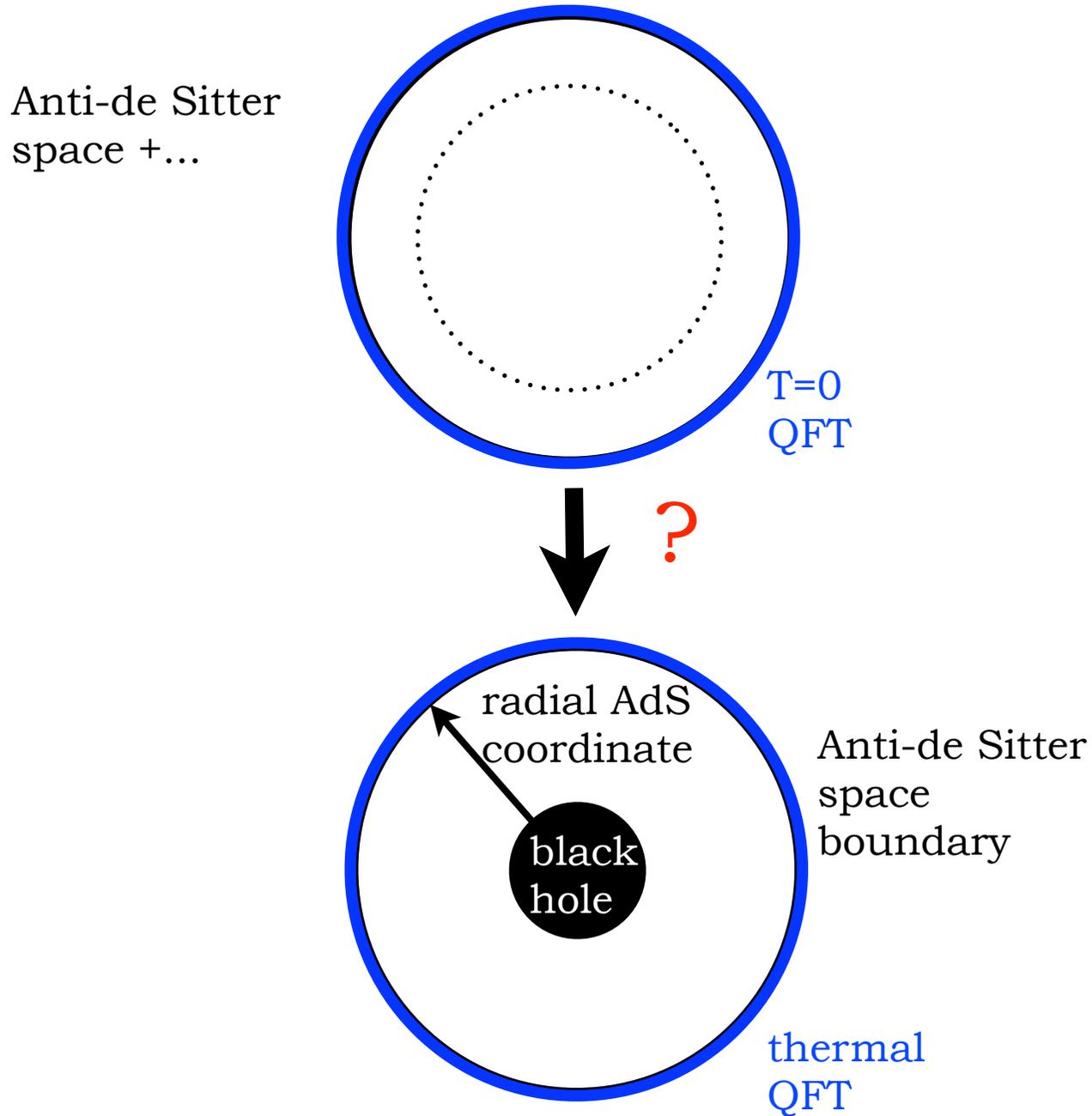


Holographic thermalization

Anti-de Sitter
space +...

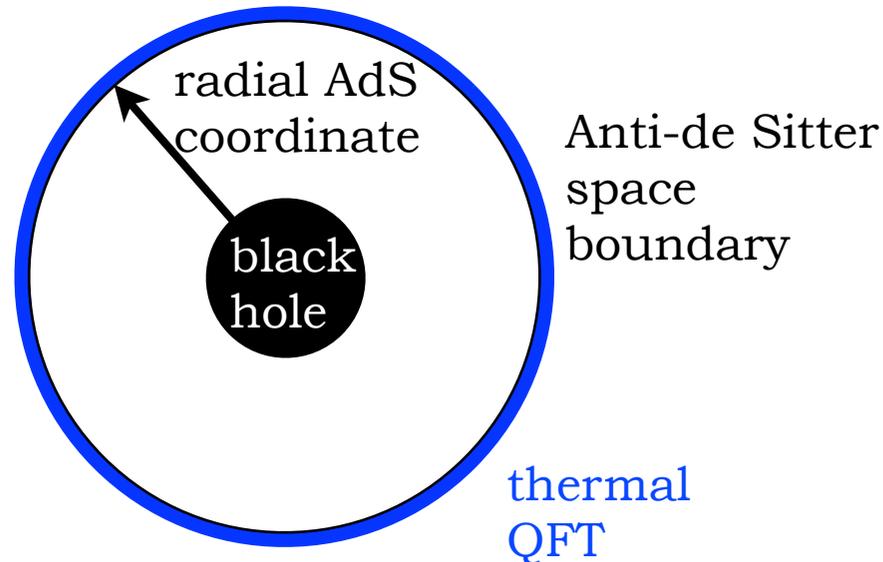
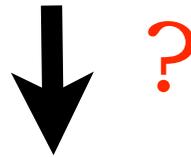
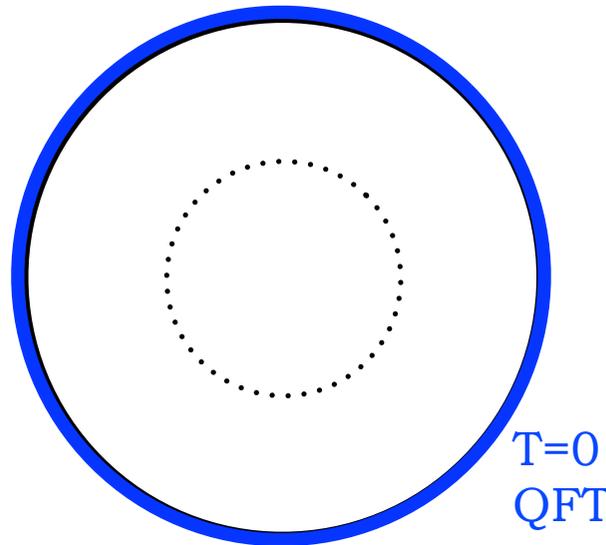


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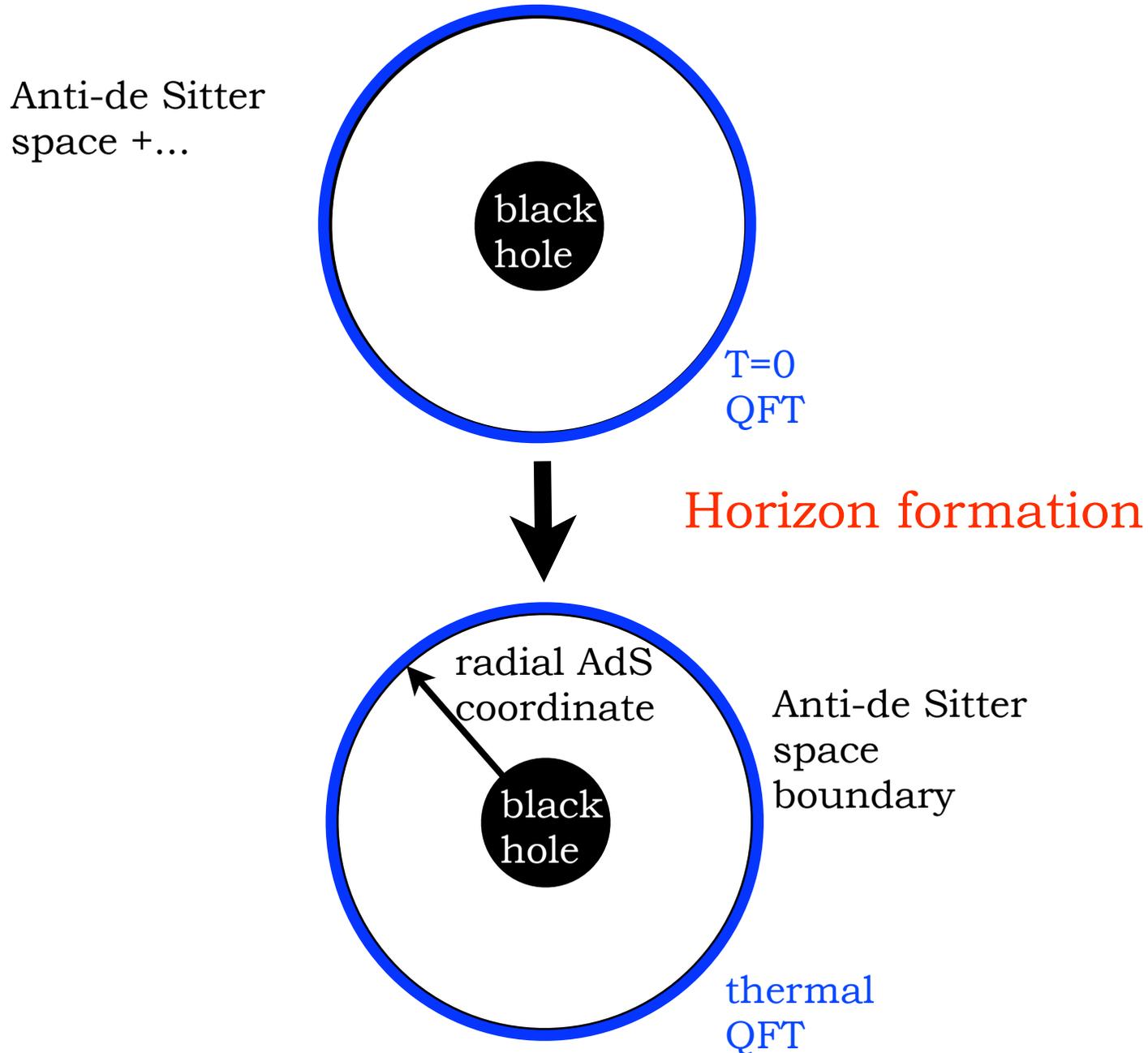


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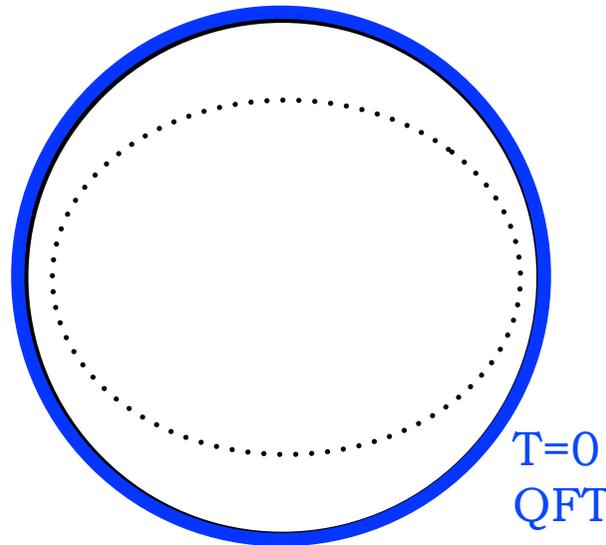


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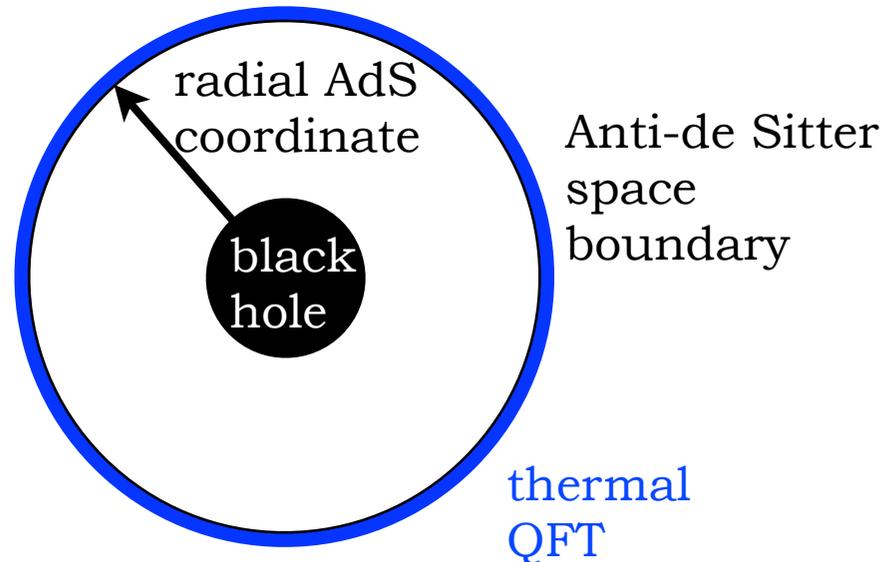


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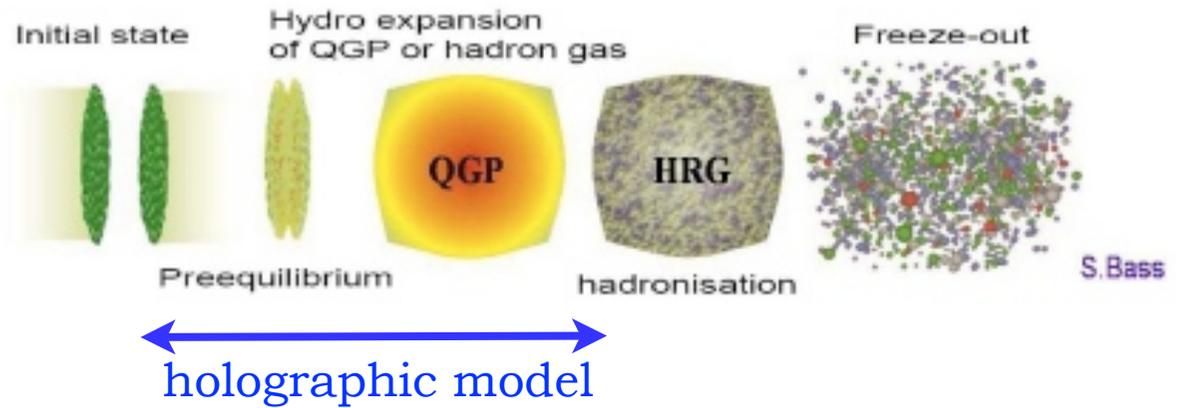


Horizon formation



Colliding shock waves in AdS

*Method II:
numerical computation
in gravity*



Colliding shock waves in AdS

$$0 = \Sigma^2 \left[\frac{1}{2}(F')^2 - \Sigma \right], \quad (2i)$$

$$0 = \Sigma^2 [F'' - 2(d_3 B)' - 3B' d_3 B] + 4\Sigma' d_3 \Sigma - \Sigma [3\Sigma' F' + 4(d_3 \Sigma)' + 6B' d_3 \Sigma], \quad (2j)$$

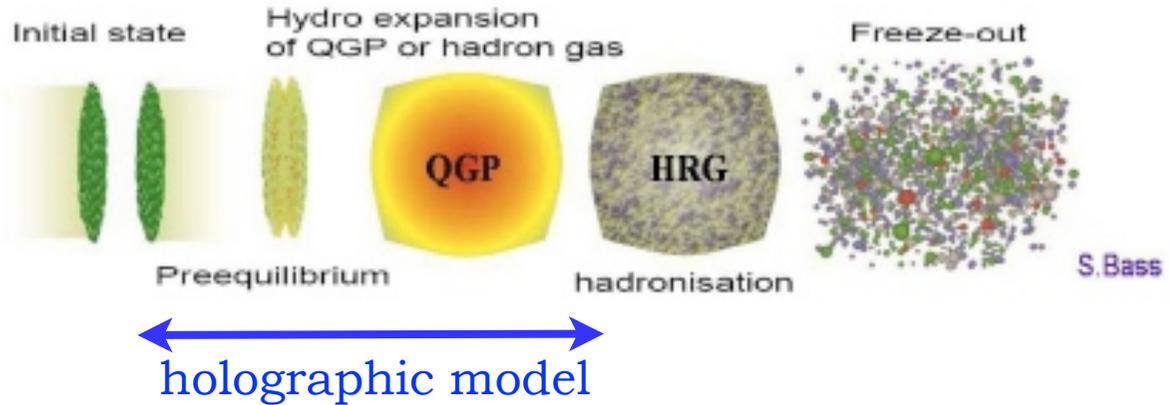
$$0 = \Sigma^4 [A'' + 3B' d_+ B + 4] - 12\Sigma^2 \Sigma' d_+ \Sigma + e^{2B} \left\{ \Sigma^2 \left[\frac{1}{2}(F')^2 - \frac{7}{2}(d_3 B)^2 - 2d_3^2 B \right] + 2(d_3 \Sigma)^2 - 4\Sigma [2(d_3 B) d_3 \Sigma + d_3^2 \Sigma] \right\}, \quad (2k)$$

$$0 = 6\Sigma^3 (d_+ \Sigma)' + 12\Sigma^2 (\Sigma' d_+ \Sigma - \Sigma^2) - e^{2B} \left\{ 2(d_3 \Sigma)^2 + \Sigma^2 \left[\frac{1}{2}(F')^2 + (d_3 F)' + 2F' d_3 B - \frac{7}{2}(d_3 B)^2 - 2d_3^2 B \right] + \Sigma [(F' - 8d_3 B) d_3 \Sigma - 4d_3^2 \Sigma] \right\}. \quad (2l)$$

$$0 = 6\Sigma^4 (d_+ B)' + 9\Sigma^3 (\Sigma' d_+ B + B' d_+ \Sigma) + e^{2B} \left\{ \Sigma^2 [(F')^2 + 2(d_3 F)' + F' d_3 B - (d_3 B)^2 - d_3^2 B] + 4(d_3 \Sigma)^2 - \Sigma [(4F' + d_3 B) d_3 \Sigma + 2d_3^2 \Sigma] \right\}, \quad (2e)$$

$$0 = 6\Sigma^2 d_+^2 \Sigma - 3\Sigma^2 A' d_+ \Sigma + 3\Sigma^3 (d_+ B)^2 - e^{2B} \left\{ (d_3 \Sigma + 2\Sigma d_3 B)(2d_+ F + d_3 A) + \Sigma [2d_3 (d_+ F) + d_3^2 A] \right\}, \quad (2f)$$

$$0 = \Sigma [2d_+ (d_3 \Sigma) + 2d_3 (d_+ \Sigma) + 3F' d_+ \Sigma] + \Sigma^2 [d_+ (F') + d_3 (A') + 4d_3 (d_+ B) - 2d_+ (d_3 B)] + \Sigma^3 (\Sigma' d_+ B + 2d_3 \Sigma) d_+ B - 4(d_3 \Sigma)^2 \Sigma, \quad (2g)$$



[Chesler, Yaffe; PRL (2011)]



Colliding shock waves in AdS

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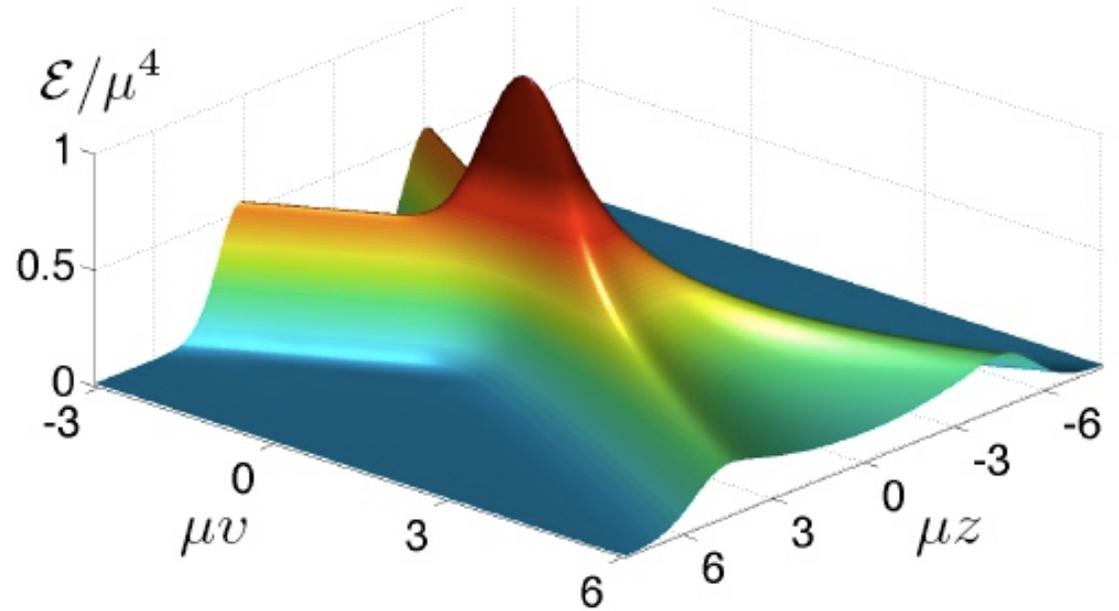
$$0 = \Sigma^4 [A'' + 3B' d_+ B + 4] - 12\Sigma^2 \Sigma' d_+ \Sigma \\ + e^{2B} \left\{ \Sigma^2 \left[\frac{1}{2}(F')^2 - \frac{7}{2}(d_3 B)^2 - 2d_3^2 B \right] \right. \\ \left. + 2(d_3 \Sigma)^2 - 4\Sigma [2(d_3 B) d_3 \Sigma + d_3^2 \Sigma] \right\}, \quad (2c)$$

$$0 = 6\Sigma^3 (d_+ \Sigma)' + 12\Sigma^2 (\Sigma' d_+ \Sigma - \Sigma^2) - e^{2B} \left\{ 2(d_3 \Sigma)^2 \right. \\ \left. + \Sigma^2 \left[\frac{1}{2}(F')^2 + (d_3 F)' + 2F' d_3 B - \frac{7}{2}(d_3 B)^2 - 2d_3^2 B \right] \right. \\ \left. + \Sigma [(F' - 8d_3 B) d_3 \Sigma - 4d_3^2 \Sigma] \right\}. \quad (2d)$$

$$0 = 6\Sigma^4 (d_+ B)' + 9\Sigma^3 (\Sigma' d_+ B + B' d_+ \Sigma) \\ + e^{2B} \left\{ \Sigma^2 [(F')^2 + 2(d_3 F)' + F' d_3 B - (d_3 B)^2 - d_3^2 B] \right. \\ \left. + 4(d_3 \Sigma)^2 - \Sigma [(4F' + d_3 B) d_3 \Sigma + 2d_3^2 \Sigma] \right\}, \quad (2e)$$

$$0 = 6\Sigma^2 d_+^2 \Sigma - 3\Sigma^2 A' d_+ \Sigma + 3\Sigma^3 (d_+ B)^2 \\ - e^{2B} \left\{ (d_3 \Sigma + 2\Sigma d_3 B)(2d_+ F + d_3 A) \right. \\ \left. + \Sigma [2d_3 (d_+ F) + d_3^2 A] \right\}, \quad (2f)$$

$$0 = \Sigma [2d_+ (d_3 \Sigma) + 2d_3 (d_+ \Sigma) + 3F' d_+ \Sigma] \\ + \Sigma^2 [d_+ (F') + d_3 (A') + 4d_3 (d_+ B) - 2d_+ (d_3 B)] \\ + 2\Sigma (\Sigma' d_+ B + 2d_3 \Sigma) d_+ B - 4(d_3 \Sigma)^2 \Sigma, \quad (2g)$$



[Chesler, Yaffe; PRL (2011)]



Colliding shock waves in AdS

$$0 = \Sigma^2 \left[\frac{1}{2}(F')^2 - \Sigma \right], \quad (2a)$$

$$0 = \Sigma^2 [F'' - 2(d_3 B)' - 3B' d_3 B] + 4\Sigma' d_3 \Sigma - \Sigma [3\Sigma' F' + 4(d_3 \Sigma)' + 6B' d_3 \Sigma], \quad (2b)$$

$$0 = \Sigma^4 [A'' + 3B' d_+ B + 4] - 12\Sigma^2 \Sigma' d_+ \Sigma + e^{2B} \left\{ \Sigma^2 \left[\frac{1}{2}(F')^2 - \frac{7}{2}(d_3 B)^2 - 2d_3^2 B \right] + 2(d_3 \Sigma)^2 - 4\Sigma [2(d_3 B) d_3 \Sigma + d_3^2 \Sigma] \right\}, \quad (2c)$$

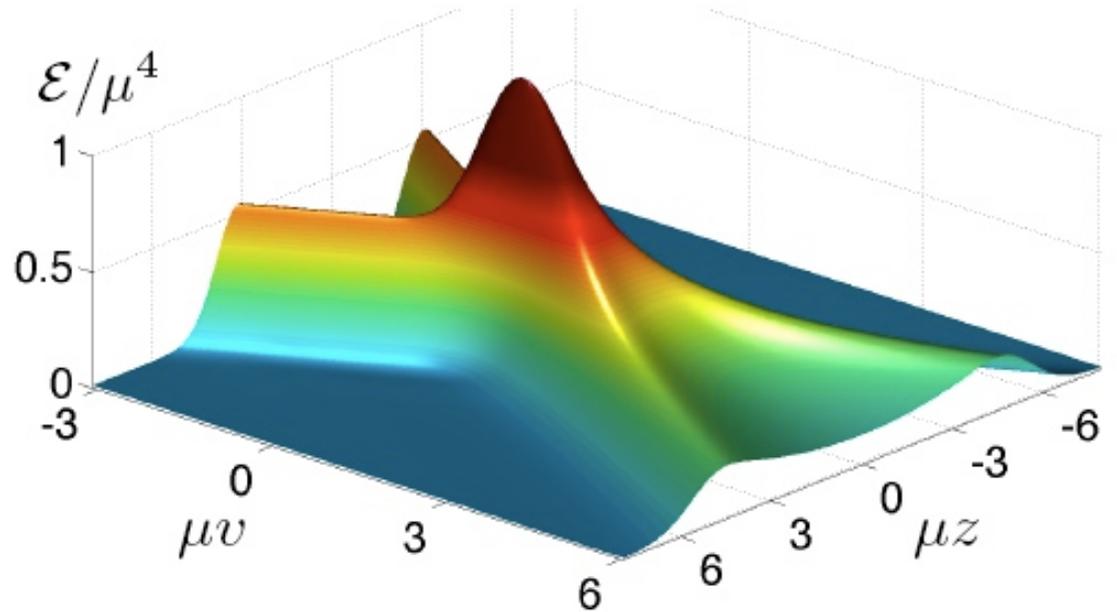
$$0 = 6\Sigma^3 (d_+ \Sigma)' + 12\Sigma^2 (\Sigma' d_+ \Sigma - \Sigma^2) - e^{2B} \left\{ 2(d_3 \Sigma)^2 + \Sigma^2 \left[\frac{1}{2}(F')^2 + (d_3 F)' + 2F' d_3 B - \frac{7}{2}(d_3 B)^2 - 2d_3^2 B \right] + \Sigma [(F' - 8d_3 B) d_3 \Sigma - 4d_3^2 \Sigma] \right\}, \quad (2d)$$

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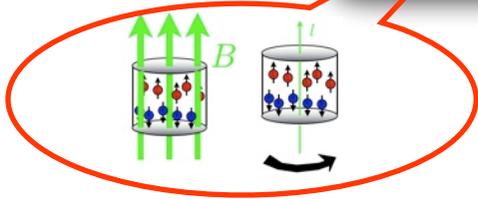
$$0 = \Sigma [2d_+ (d_3 \Sigma) + 2d_3 (d_+ \Sigma) + 3F' d_+ \Sigma] + \Sigma^2 [d_+ (F') + d_3 (A') + 4d_3 (d_+ B) - 2d_+ (d_3 B)] - 2\Sigma (\Sigma' d_+ B + 2d_3 \Sigma) d_+ B - 4(d_3 \Sigma)^2, \quad (2g)$$

[Chesler, Yaffe; PRL (2011)]



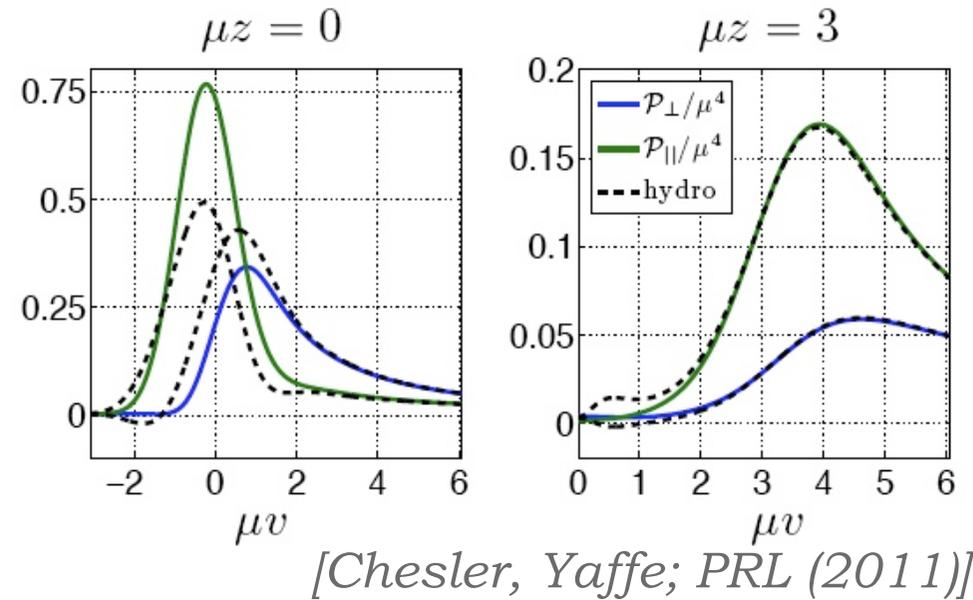
- more power
- Einstein-Maxwell-Chern-Simons equations

[Fuini, MK, Yaffe (...)]

Questions for our model thermalization

Chiral effects?



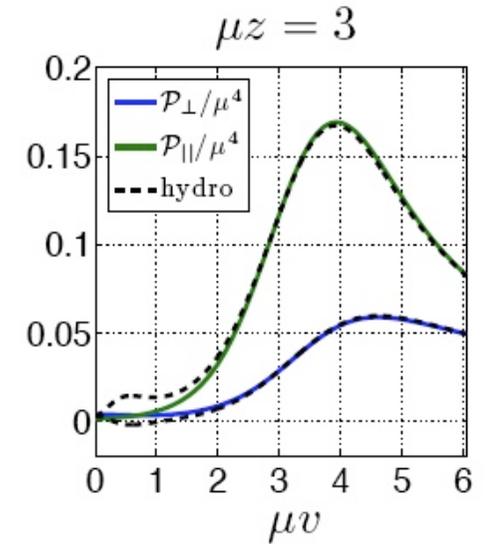
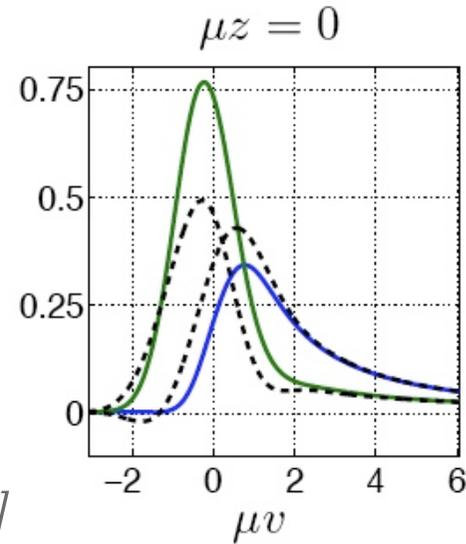
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Thermalization, isotropization
or hydroization?

[Caron-Huot, Chesler, Teaney; PRD (2011)]

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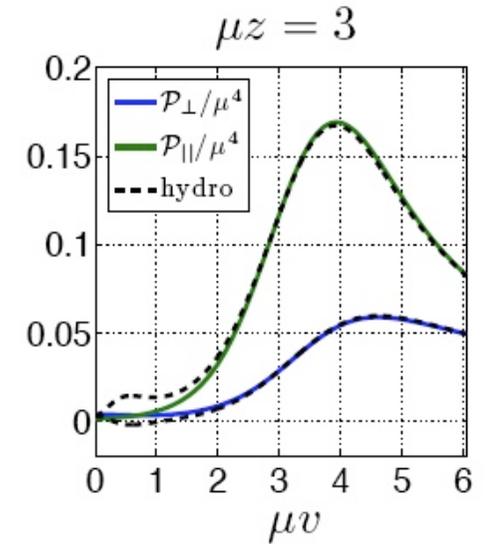
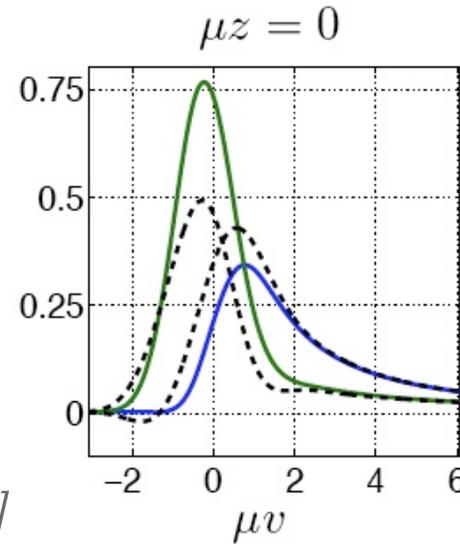


Questions for our model thermalization

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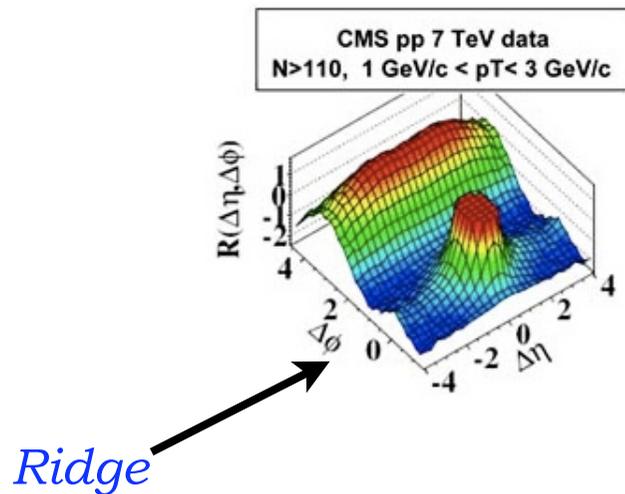
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[Chesler, Yaffe; PRL (2011)]

What generates the ridge at
RHIC and LHC?

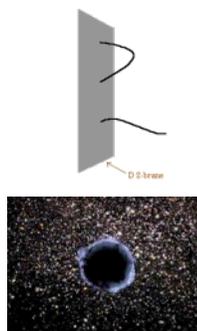


- ✓ non-equilibrium model of heavy ion collision
- ✓ thermal two-point functions



Navigator

- I. Discovering the chiral vortical effect
- II. Formal discoveries in an old theory: relativistic hydrodynamics with anomalies
- III. Thermalization: non-equilibrium models
- IV. Putting strings to use



Claims

“String theory is the unique consistent well-defined theory of everything.”

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well-defined ~~theory of~~ everything.”

Claims

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well-defined ~~theory of~~ everything.”

Claims

“String theory is the consistent well-defined everything.”

A bag full of perfect models

String theories are

- well-defined
- consistent
- causal
- unitary
- UV-complete
- often solvable
- giving you “all there is”



- often overly simple
- missing properties
- extra properties



A bag full of perfect models

String theories are

- well-defined
- consistent
- causal
- unitary
- UV-complete
- often solvable
- giving you “all there is”

Effective field theories are

- possibly violating principles
- always incomplete
- biased/intuition



- often overly simple
- missing properties
- extra properties

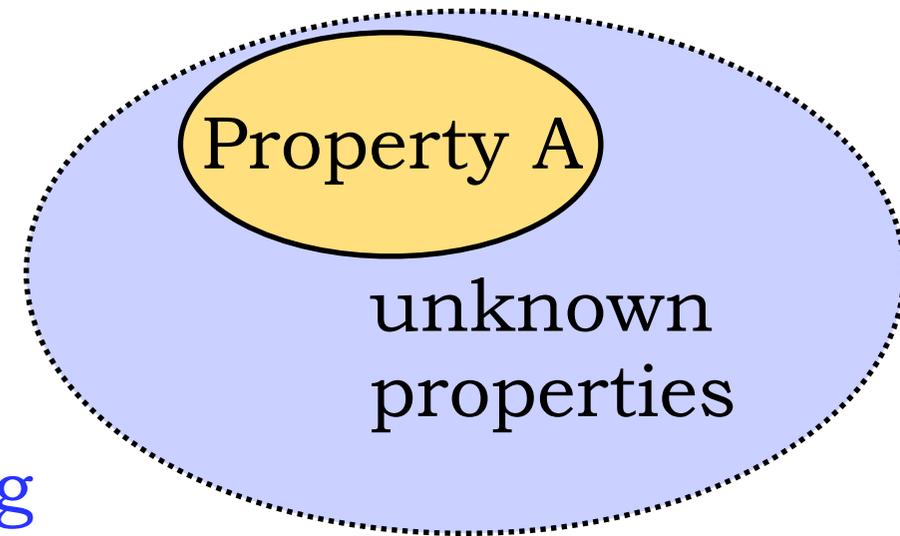
- just simple enough
- relevant properties
- tailor-made



Top-down versus bottom-up

Bottom-up models are

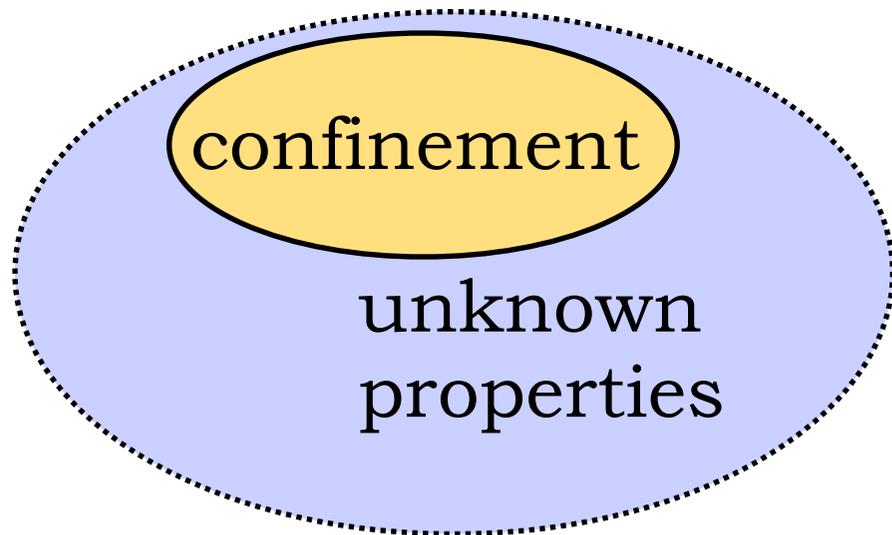
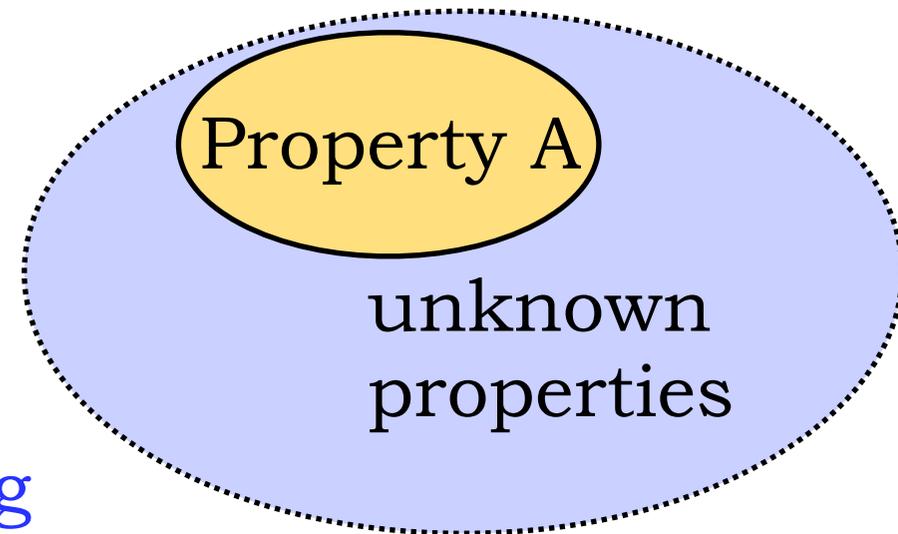
- initially useful
- incomplete
- ill-defined
- often **inconsistent**
- **possibly causality violating**



Top-down versus bottom-up

Bottom-up models are

- initially useful
- incomplete
- ill-defined
- often **inconsistent**
- **possibly causality violating**



Example: “AdS/QCD”

- not UV-complete
- incomplete
- field theory dual unknown

Top-down constructions are necessary.



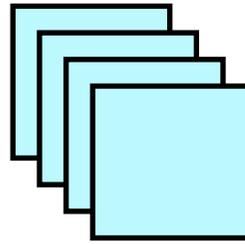
Only known top-down setting: string theory

Original: *AdS/CFT*

Two distinct ways to describe this stack:

4-dimensional worldvolume theory on the D3-branes
(e.g. $\mathcal{N} = 4$ Super-Yang-Mills in 3+1 dimensions)

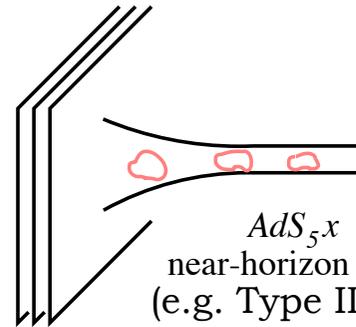
gauge theory



Stack of N **D3-branes** (coincident) in 10 dimensions



duality



$AdS_{5,x} S^5$
near-horizon geometry
(e.g. Type II B Supergravity with 5-form flux N through the 5-sphere)

string theory



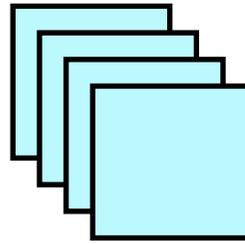
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string theory

Add/change geometric objects on 'string theory side'.

Example: Schwarzschild radius corresponds to temperature



“Everything” at strong coupling???



Empirical evidence

QCD, nuclear theory,
heavy ion collisions

“Holographic Vector Mesons from Spectral Functions at finite Baryon or Isospin Density” PRD (2007)

...

“Sum Rules from an Extra Dimension JHEP (2011)”

...

condensed matter physics

“Hydrodynamics of Holographic Superconductors, JHEP (2009)”

...

formal insights

“Towards Hydrodynamics without an Entropy Current” PRL (2012)

...

gauge/gravity concepts

“Holographic Operator Mixing and Quasinormal Modes on the Brane, JHEP (2010)”

...

- ✓ Formal investigation of fundamental principles.
- ✓ Make predictions to be compared to experiments.



Summary

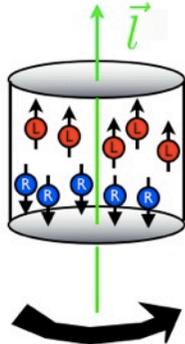


Summary

Chiral vortical effect

[Erdmenger, Haack, MK, Yarom; JHEP (2009)]

Holographic model of relativistic quantum fluid



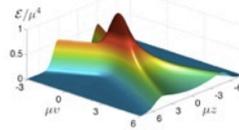
later: field theory understanding

[Son, Surówka; PRL (2009)]

Holographic model of Heavy ion collision

Quantum fluid far-from-equilibrium with anomaly

[Fuini, MK, Yaffe (...)]



[Chesler, Yaffe; PRL (201)]

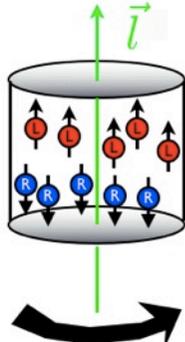
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Summary

Chiral vortical effect
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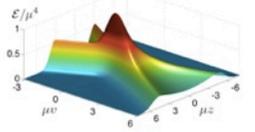
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[Chesler, Yaffe; PRL (201)]

 Matthias Kaminski *A Theory of Everything at Strong Coupling* Page 6

Conclusions

- ➔ string theory is a bag full of perfect models
- ➔ **holography reveals structures** in these
- ➔ effective field theories are often imperfect
- ➔ bottom-up holographic models are of limited use
- ➔ aim for “perfect” EFTs inspired by string models
- ➔ **experiments!**



Outlook

Investigate systems

- at **strong** coupling
- in **topological phases**
- **far-from-equilibrium**
- compare structure observables **to experiments**

Lines of research:

I) *Nuclear Physics & Particle Physics*: toy model of a **heavy-ion-collision & correlations**

II) *Effective Field Theory*: most general hydrodynamics with **anomalies**, other EFTs

III) *Condensed Matter Physics*: Examination and classification of **topological phases**



1st Karl Schwarzschild Meeting KSM2013

July 22. - 26., 2013 at FIAS Frankfurt, Germany

<http://fias.uni-frankfurt.de/ksm2013/>

S. Gubser
A. Karch
R. Mann
R. Myers

L. Susskind
H. Verlinde
R. Wald
...



HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

Weekend Meeting: QCD Phase Diagram & Holography

July 27./28., 2013 at FIAS Frankfurt, Germany

<http://fias.uni-frankfurt.de/holography/>

S. Gubser *
A. Karch
K. Landsteiner *
...



HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

